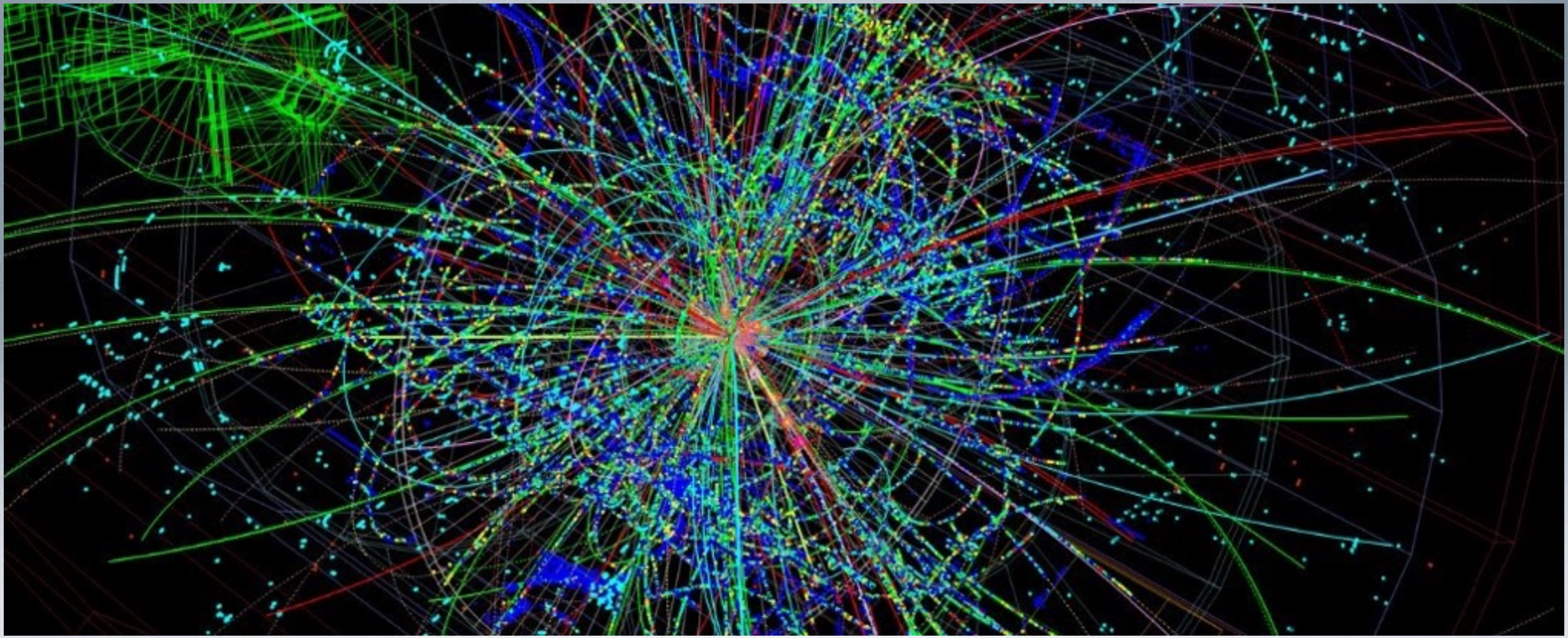
Top quark mass effects in Higgs boson pair production

Gudrun Heinrich

Max Planck Institute for Physics, Munich



LAL Orsay, December 12, 2017

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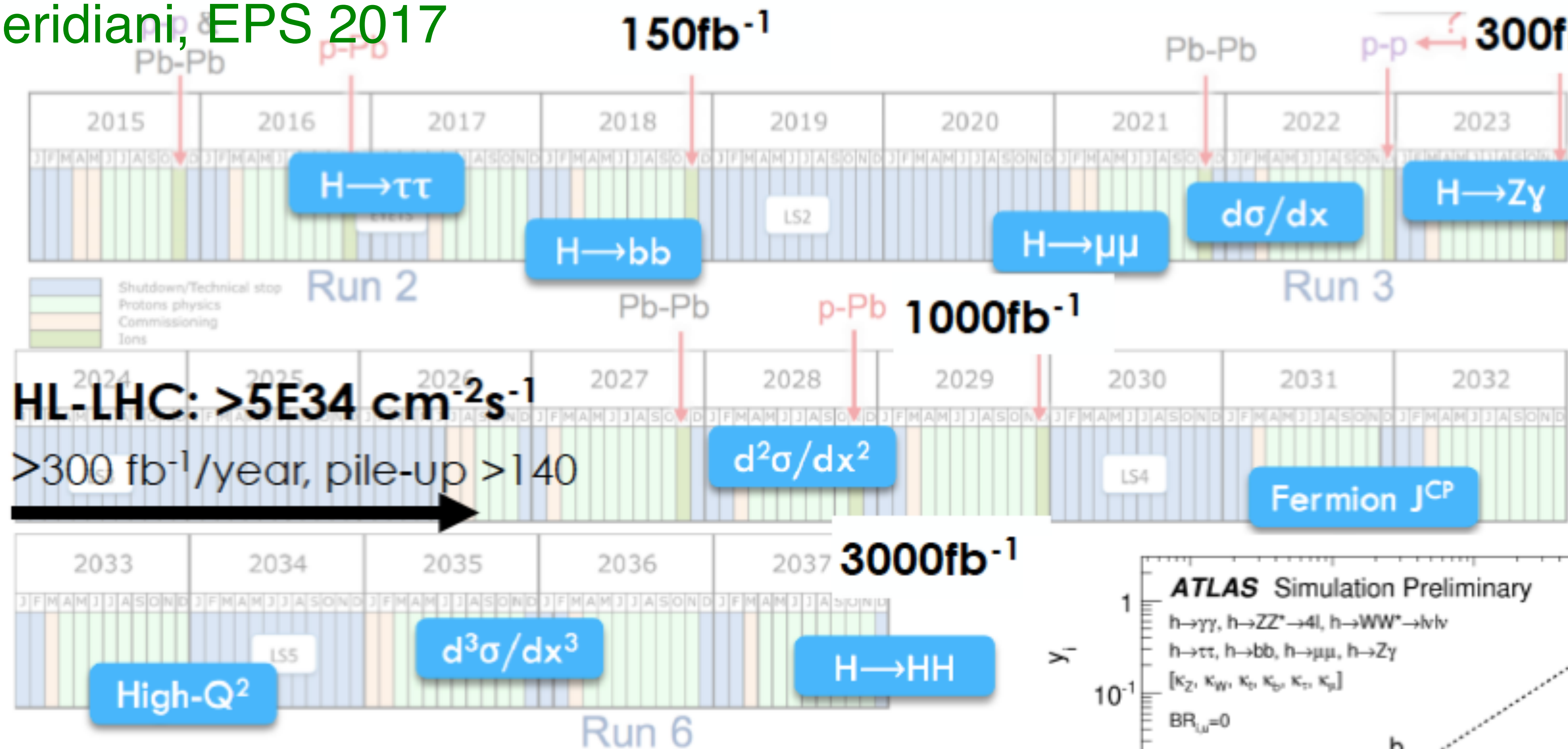
TIMELINE BEYOND RUN2

Credits: A. David @ GRC 2017

P.Meridiani, EPS 2017

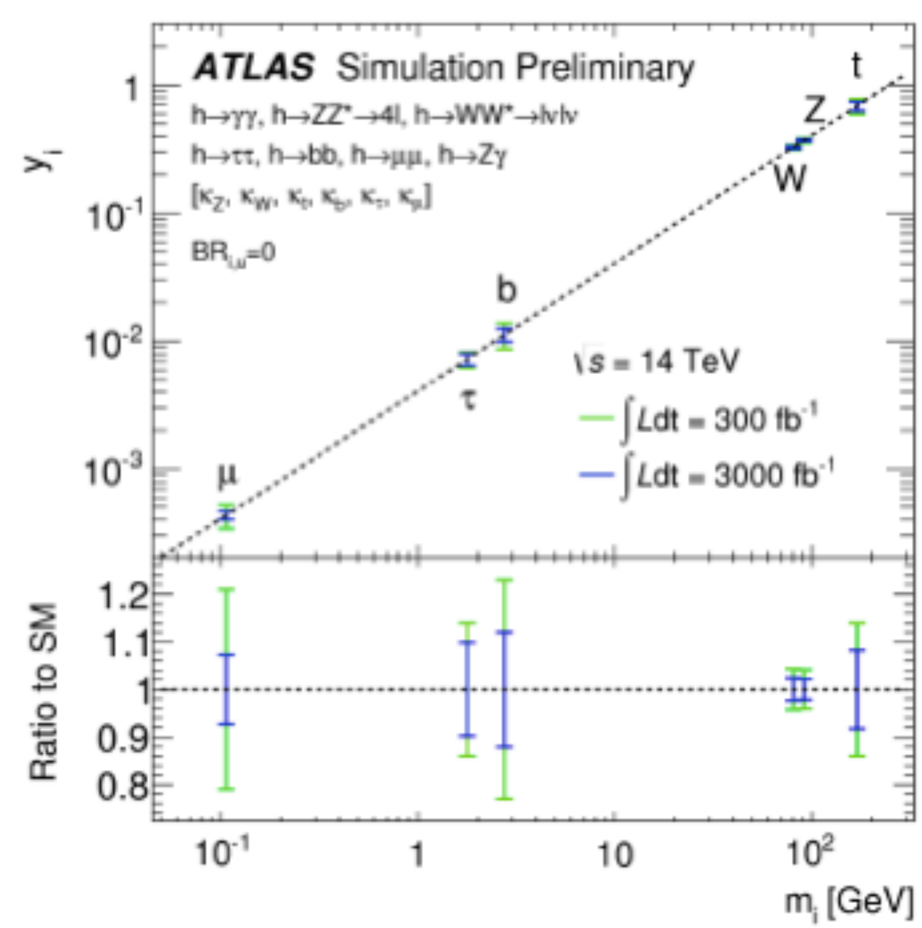


HL-LHC: >5E34 $cm^{-2}s^{-1}$

>300 fb^{-1}/year, pile-up >140

Higgs boson self-coupling:

prime candidate for
New Physics to show up



Exploring the Higgs sector

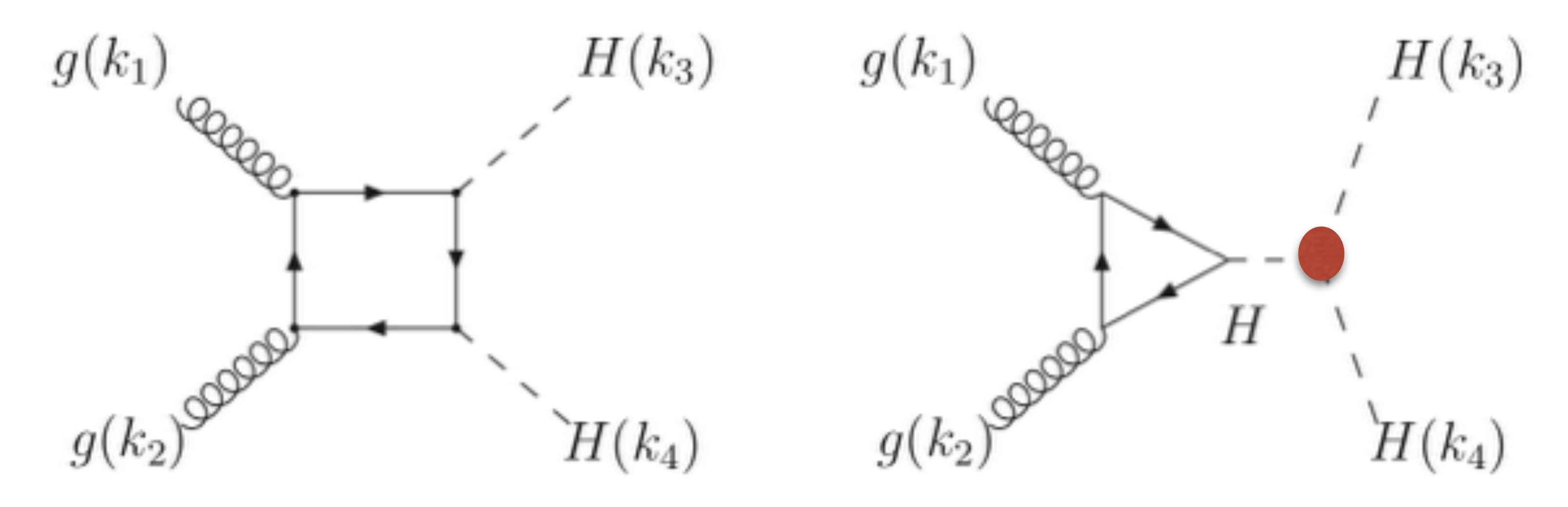
SM: $V(\Phi) = -\frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$

↓ EW symmetry breaking

$$\frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

λ_{3h} completely determined in the SM

can be measured e.g. in Higgs boson pair production

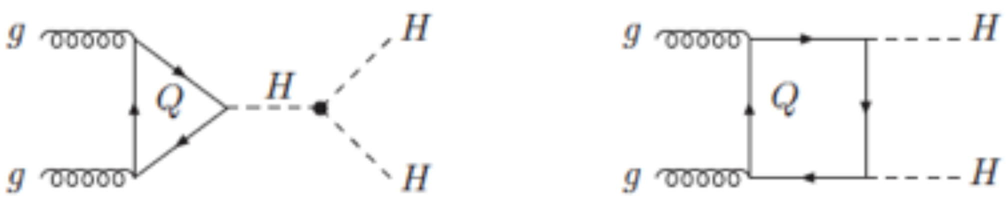


current best limit $\sigma_{HH} \leq 19\,\sigma_{HH}^{SM}$ ($b\bar{b}\gamma\gamma$ channel)

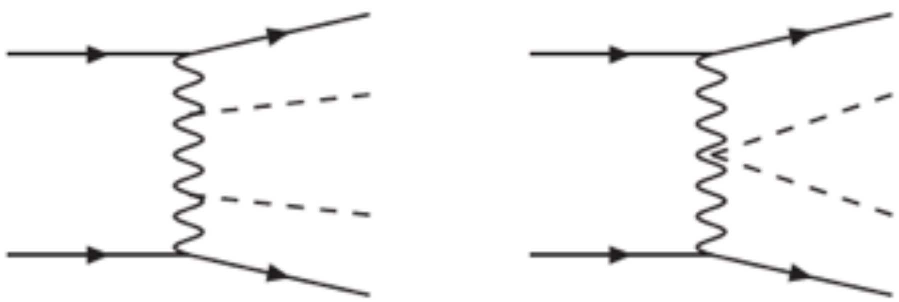
measurement of λ_{3h} only at HL-LHC

Higgs boson pair production

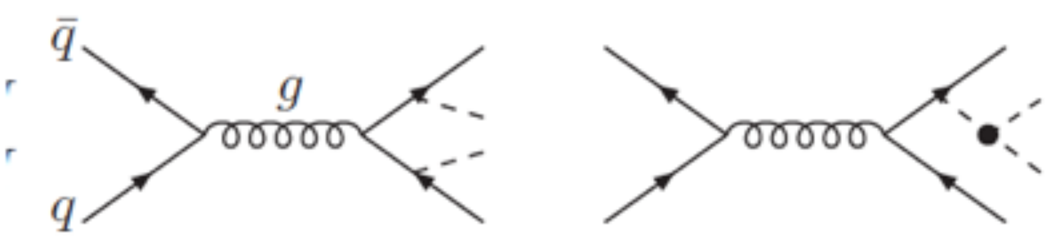
- gluon fusion



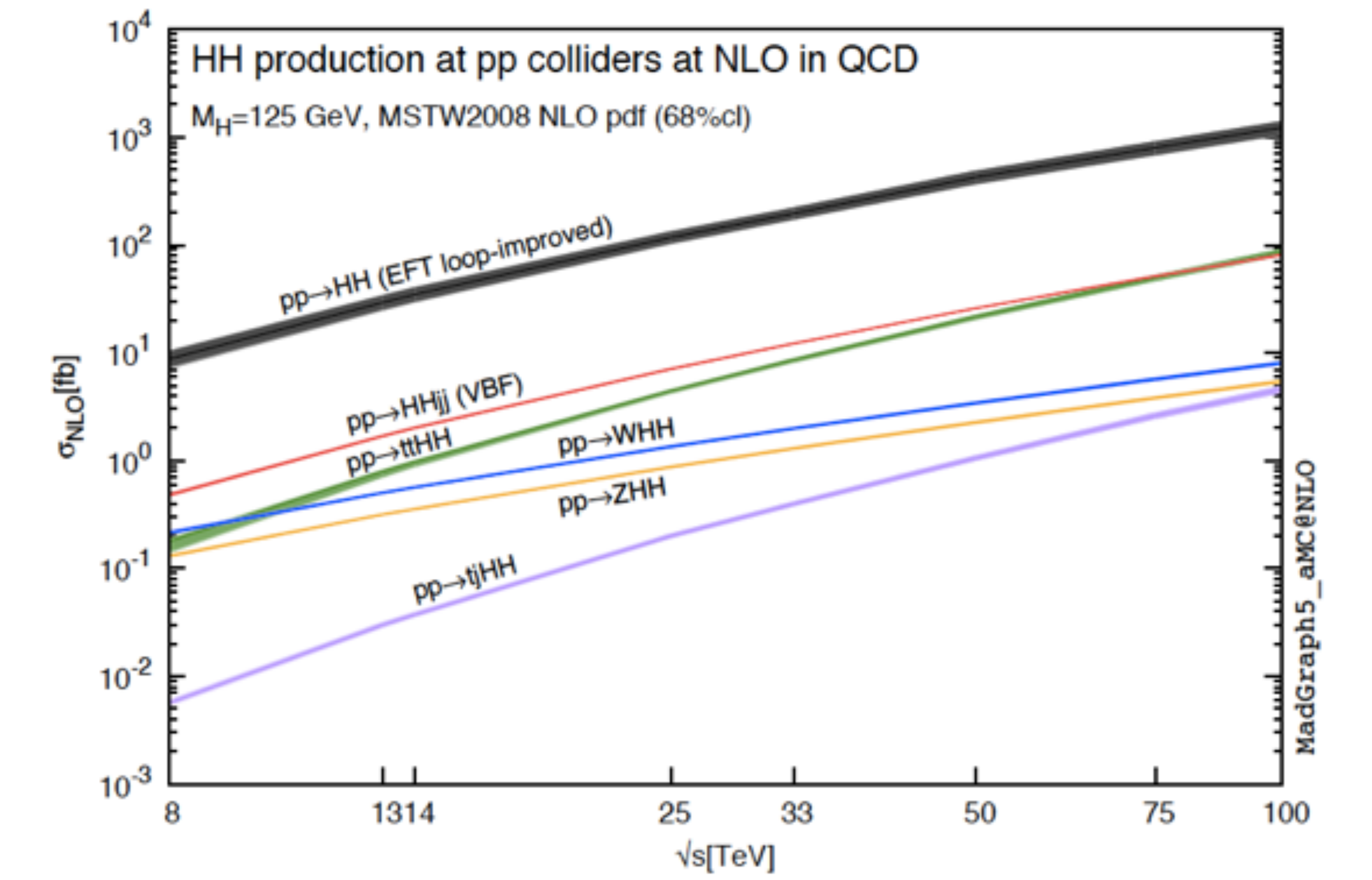
- vector boson fusion



- top-quark associated



- Higgs-strahlung



Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro ‘14

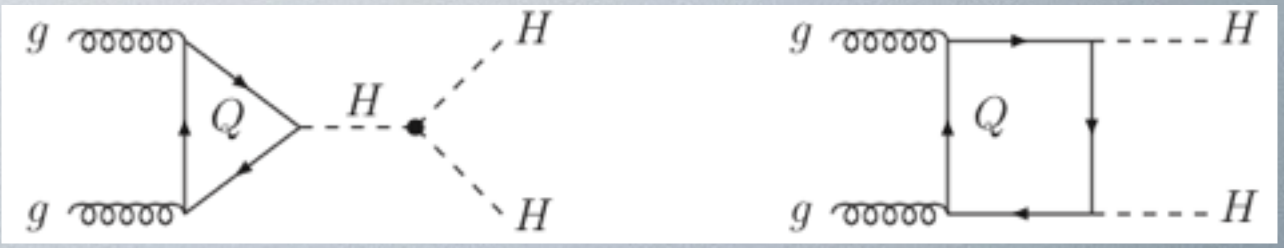
largest cross section from gluon fusion, but still

$$\sigma_{ggHH} \sim 10^{-3}\, \sigma_{ggH}$$

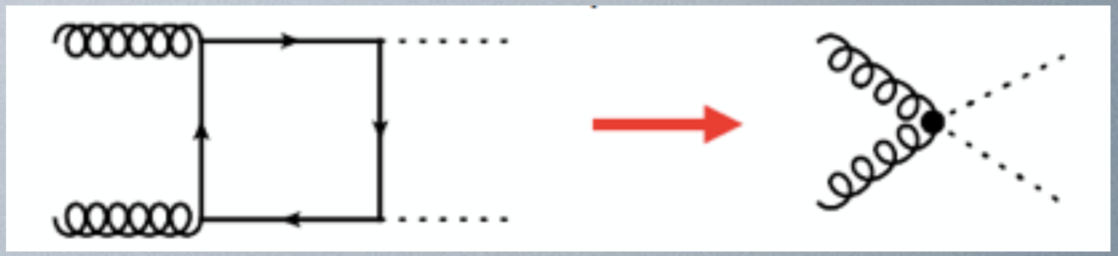
Higgs boson pair production in gluon fusion

LO with full heavy quark mass dependence

Glover, van der Bij ’88, Plehn, Spira, Zerwas ’96



$m_t \to \infty$ limit: “Higgs Effective Field Theory” (HEFT)

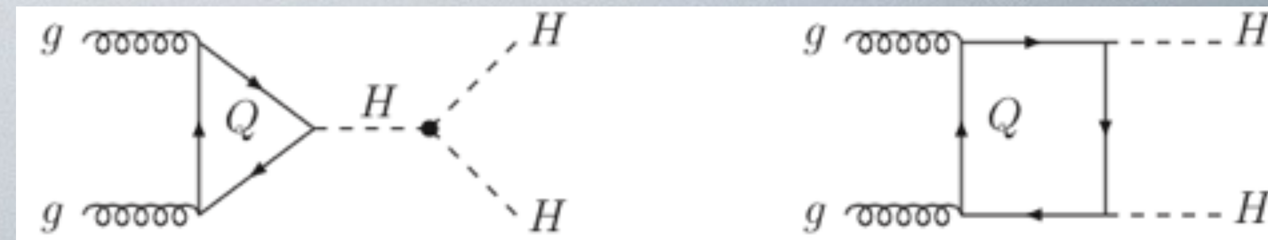


Note:

HEFT strictly valid only for $\sqrt{\hat{s}} \ll 2m_t$
HH production threshold: $2m_H < \sqrt{\hat{s}}$

$\Rightarrow$ validity of HEFT limited to $250\,\mathrm{GeV} < \sqrt{\hat{s}} < 340\,\mathrm{GeV}$

Higgs boson pair production in gluon fusion



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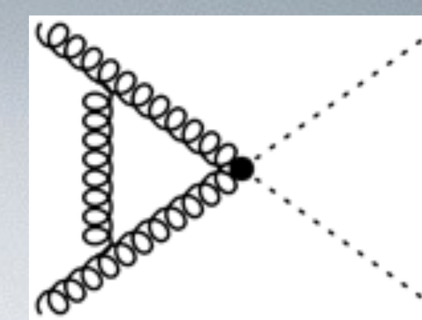
"Born-improved NLO HEFT": rescale by $\mathcal{M}^{LO}(m_t)/\mathcal{M}^{LO}_{\mathrm{HEFT}}$

NLO in Born-improved HEFT Dawson, Dittmaier, Spira '98 (**HPAIR**) $K \simeq 2$



- **supplemented with $1/m_t$ expansion:** $(\pm 10\%)$

  Grigo, Hoff, Melnikov, Steinhauser '13, '15 ; Degrassi, Giardino, Gröber '16

- **full mass dependence in NLO real radiation ("FTapprox")** **-10%**

  Frederix, Hirschi, Mattelaer, Maltoni, Torrielli, Vryonidou, Zaro '14;
  Maltoni, Vryonidou, Zaro '14

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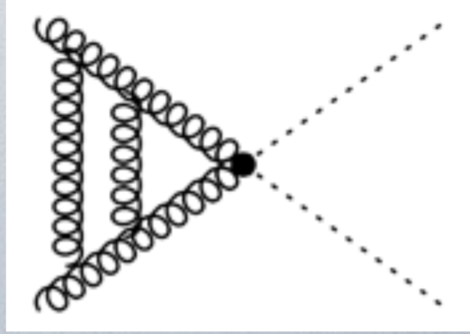
Higgs boson pair production in gluon fusion



NNLO in $m_t \to \infty$ limit: **+20%**

- **total xs NNLO** De Florian, Mazzitelli '13
- **including all matching coefficients** Grigo, Melnikov, Steinhauser '14
- **supplemented with $1/m_t$ expansion:** Grigo, Hoff, Steinhauser '15
- **soft gluon resummation NNLL** Shao, Li, Li, Wang '13; De Florian, Mazzitelli '15 **+9%**
- **differential NNLO** De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16

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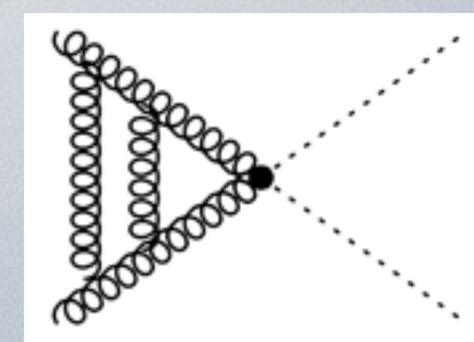

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NLO calculation with full top mass dependence

Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke '16

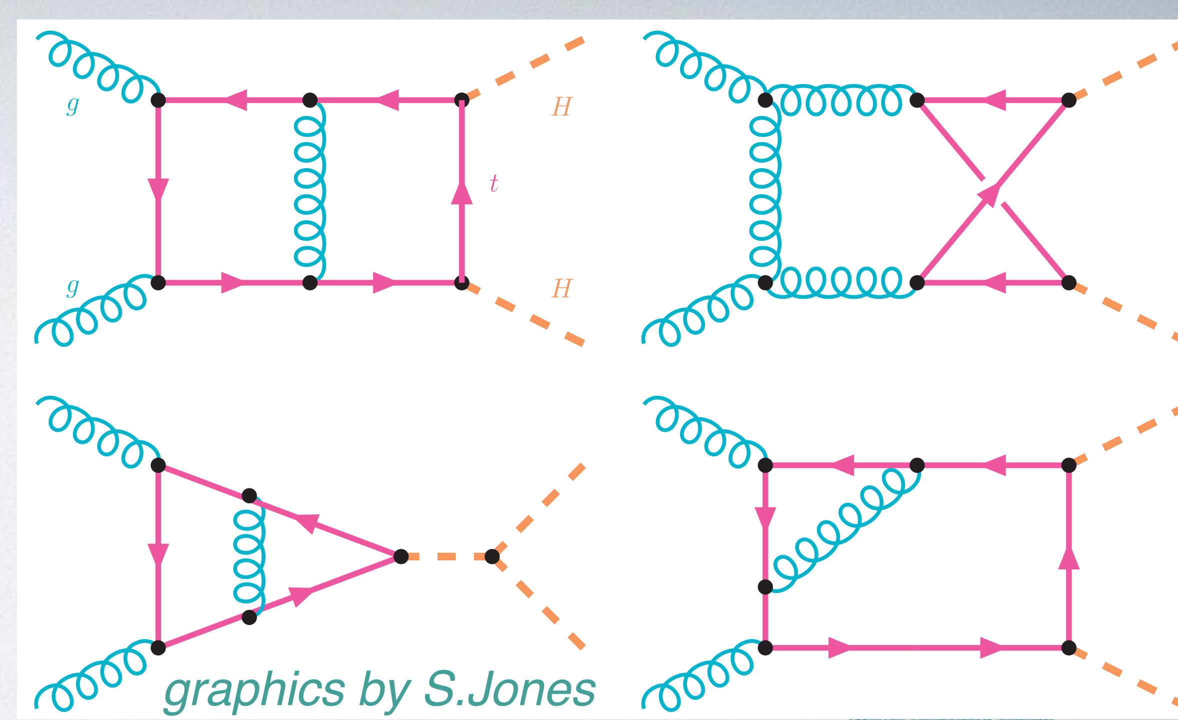
4 independent scales s12, s23, mH, mt

all integrals calculated **numerically** with

SecDec

Borowka, GH, Jones, Kerner, Schlenk, Zirke '15

Borowka, GH, Jahn, Jones, Kerner, Schlenk, Zirke '17



graphics by S.Jones

- q_T **resummation NLL+NLO**

Ferrera, Pires '16

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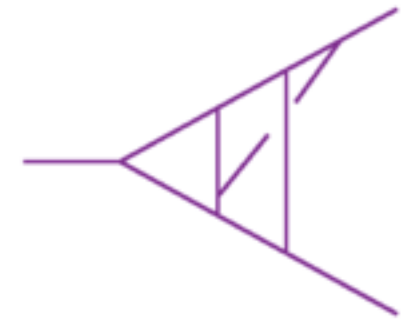
numerical evaluation of multi-loop integrals

http://secdec.hepforge.org https://github.com/mppmu/secdec/releases

SecDec is hosted by Hepforge, IPPP Durham



SecDec

Sophia Borowka, Gudrun Heinrich, Stephan Jahn, Stephen Jones, Matthias Kerner, Johannes Schlenk, Tom Zirke

A program to evaluate dimensionally regulated parameter integrals numerically

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NEW! The latest version of pySecDec is available on github. The manual is available on readthedocs.
Download the version 1.1.2 of pySecDec as pySecDec-1.1.2.tar.gz. The manual is available here.
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The first release version of pySecDec can be downloaded as pySecDec-1.0.tar.gz. The manual is available here.
See also the corresponding paper arXiv:1703.09692.

algorithm: T. Binoth, GH ‘00

version 1.0: J. Carter, GH ‘10

version 2.0: S.Borowka, J. Carter, GH ‘12

version 3.0: S.Borowka, GH, S.Jones, M.Kerner, J.Schlenk, T.Zirke ‘15

pySecDec: S.Borowka, GH, S.Jahn, S.Jones, M.Kerner, J.Schlenk, T.Zirke **‘17**

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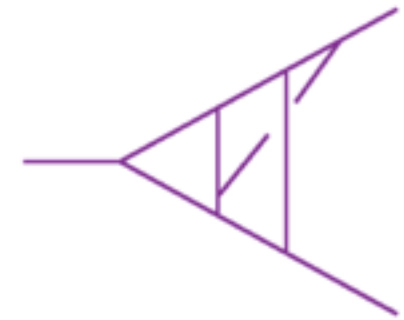

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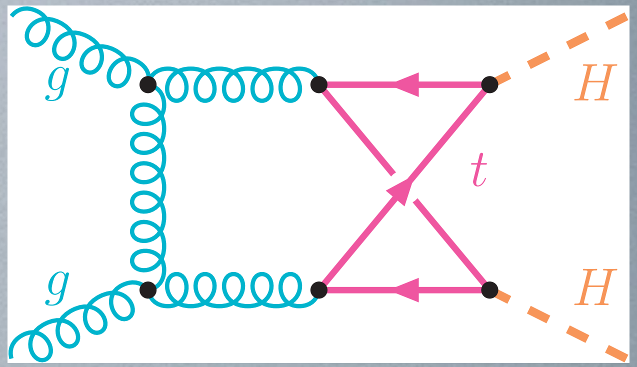
New!
can be used as an integral library

calculation: building blocks

- amplitude generation with 2 setups (custom made and “GoSam-2loop”)
- amplitude reduction with **Reduze** [C. Studerus, A. v.Manteuffel]
- integrals calculated numerically with **SecDec** (analytically unknown)

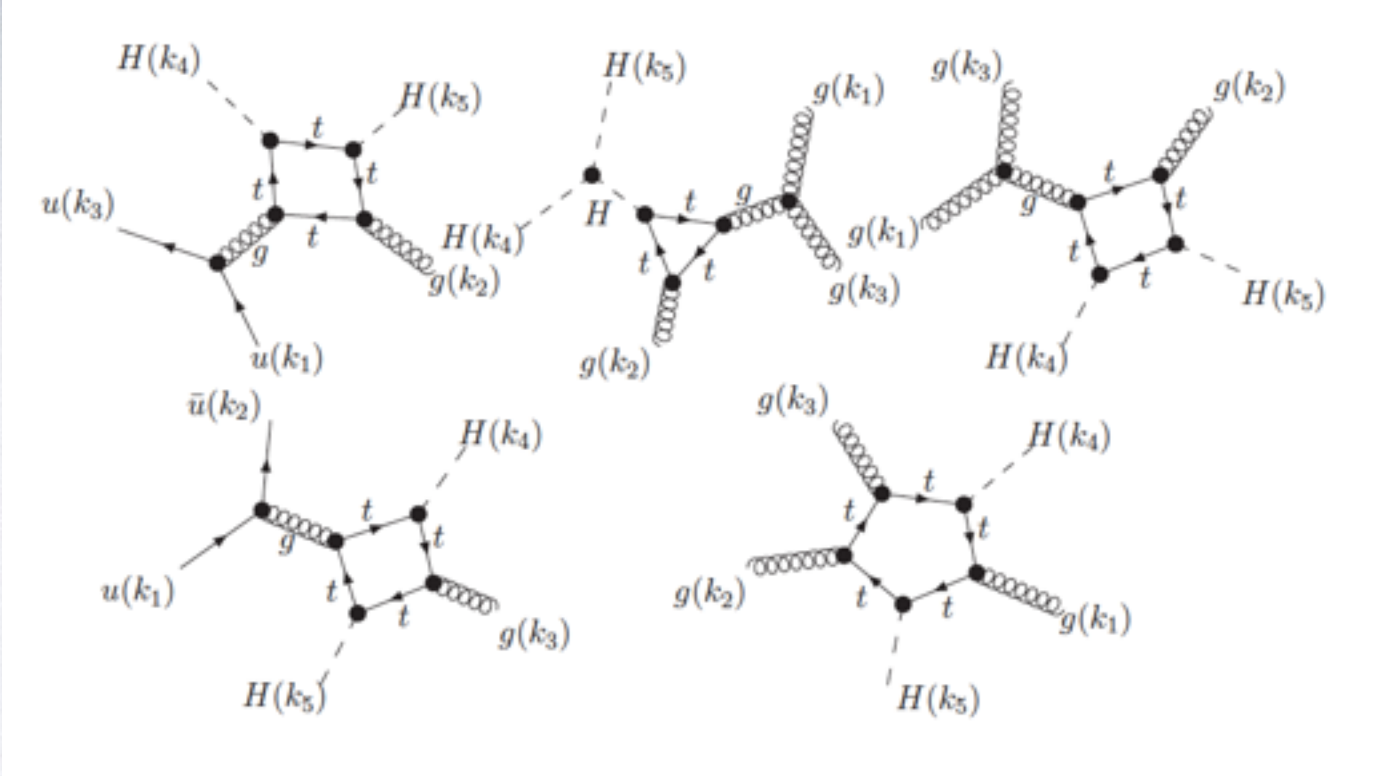


- total number of integrals:
  - before reduction: ~10000, after reduction ~330, after sector decomposition 11244 (3086 non-planar)
  - used finite basis for planar integrals

- real radiation:

  (a) GoSam-1L + Catani-Seymour dipole subtraction

  (b) GoSam-1L + POWHEG



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top mass effects

total cross sections at 14 TeV $\mu_0 = m_{HH}/2$

	$\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	$\sigma_{\rm NNLO}$[fb]
HEFT	$17.07^{+30.9\%}_{-22.2\%}$	$31.93^{+17.6\%}_{-15.2\%}$	$37.52^{+5.2\%}_{-7.6\%}$
B-i. HEFT	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	
$\rm FT_{approx}$	$19.85^{+27.6\%}_{-20.5\%}$	$34.26^{+14.7\%}_{-13.2\%}$	
full m_t dep.	$19.85^{+27.6\%}_{-20.5\%}$	$32.91^{+13.6\%}_{-12.6\%}$	

PDF4LHC15_nlo_30_pdfas

HXSWG: $\sigma'_{NNLL} = \sigma_{NNLL} + \delta_t\,\sigma^{\rm HEFT}_{NLO} = 39.64^{+4.4\%}_{-6.0\%}$

m_H=125 GeV, m_t=173 GeV

uncertainties: $\mu_{R,F} \in [\mu_0/2, 2\,\mu_0]$ (7-point variation)

top mass effects: energy dependence

$\sqrt{s}$	LO [fb]	B-i. NLO HEFT [fb]	NLO FT_{approx} [fb]	NLO [fb]
14 TeV	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$34.26^{+14.7\%}_{-13.2\%}$	$32.91^{+13.6\%}_{-12.6\%}$
27 TeV	$78.85^{+21.5\%}_{-17.0\%}$	$154.94^{+16.2\%}_{-13.4\%}$	$134.12^{+12.7\%}_{-11.1\%}$	$127.88^{+11.6\%}_{-10.5\%}$
100 TeV	$731.3^{+20.9\%}_{-15.9\%}$	$1511^{+16.0\%}_{-13.0\%}$	$1220^{+11.9\%}_{-10.7\%}$	$1149^{+10.8\%}_{-10.0\%}$

scale uncertainties

preliminary, $\pm$ 0.3 stat. uncertainty

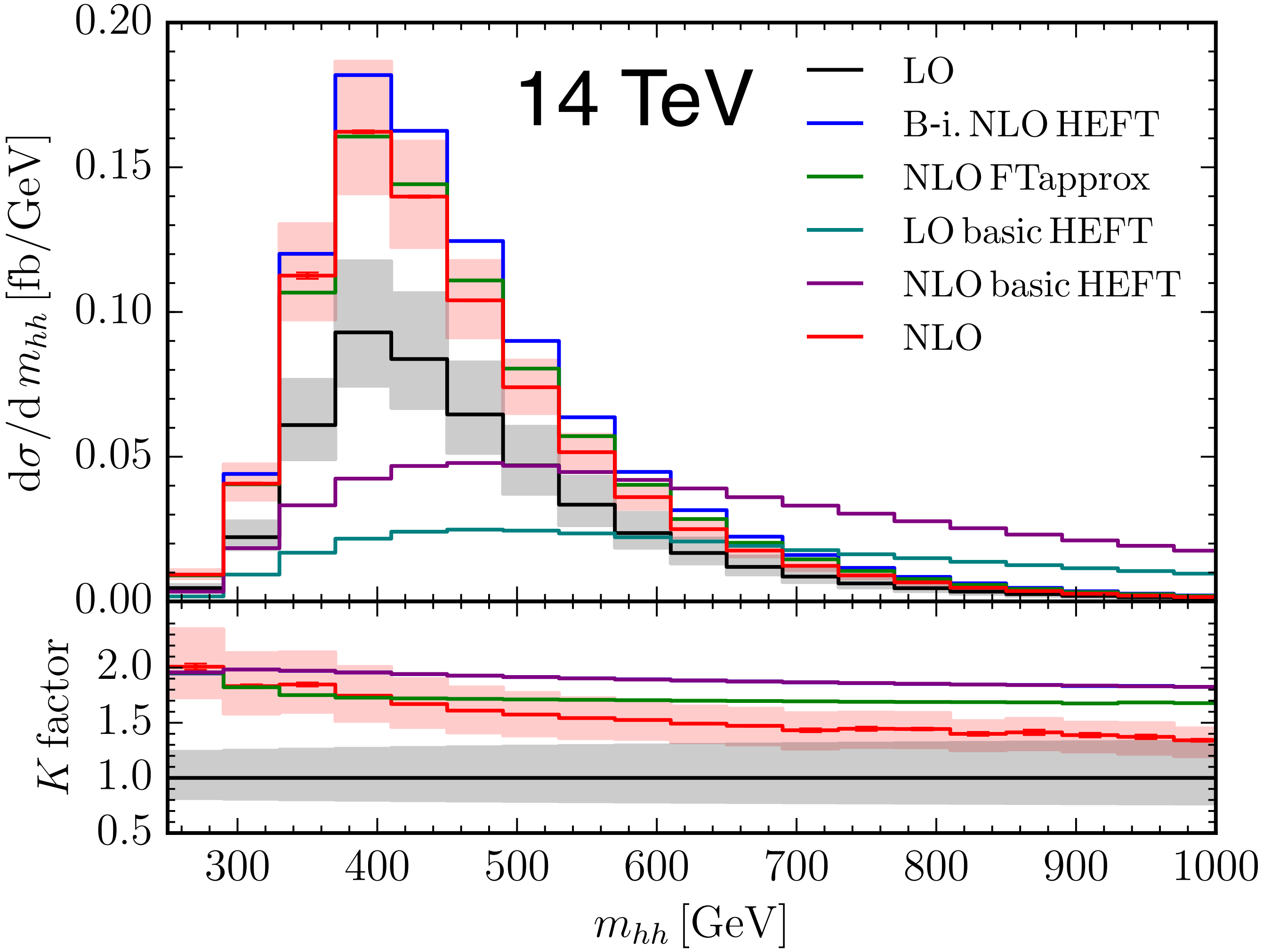
- relative difference Born-improved NLO HEFT to full NLO:

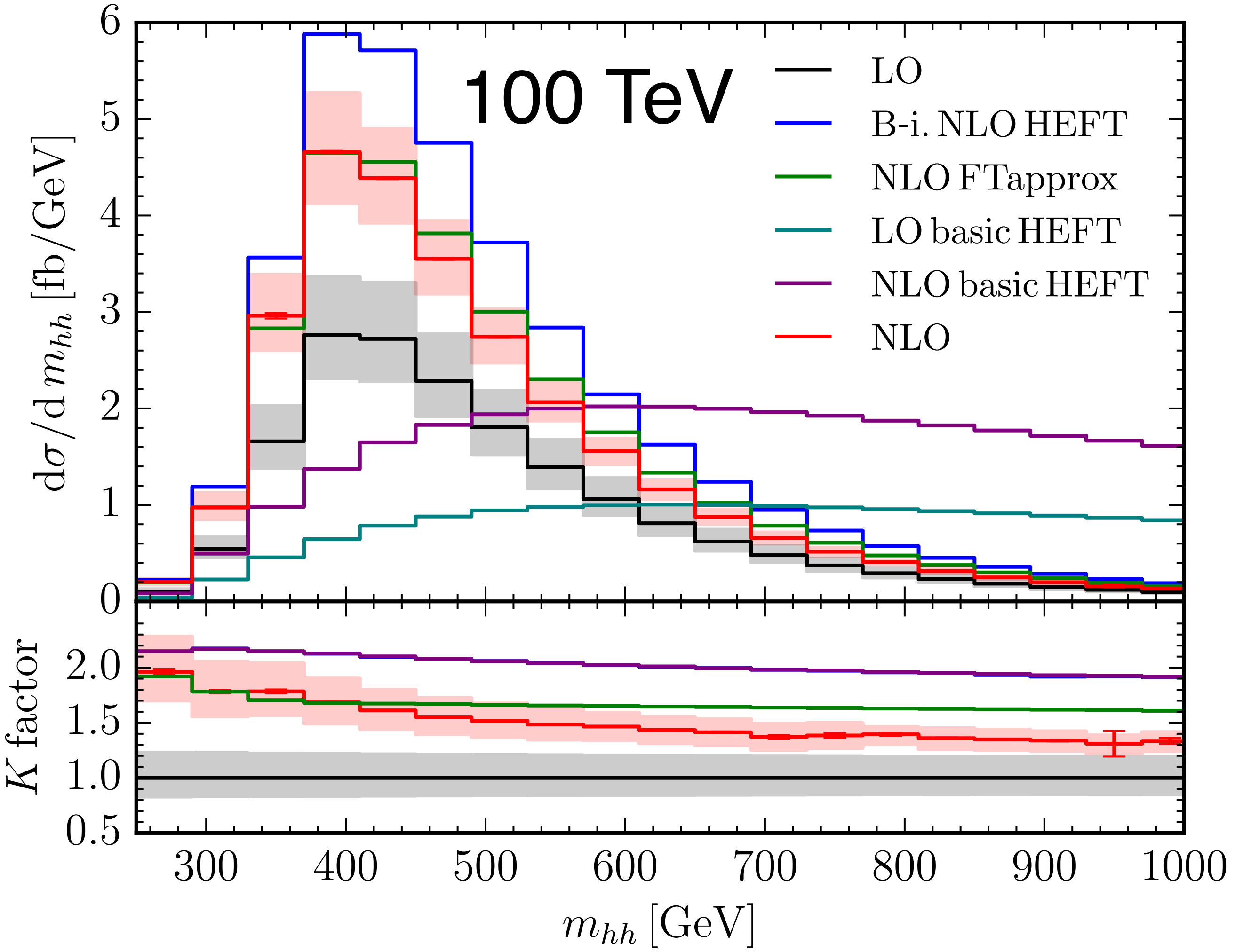
14 TeV: 16.4%

27 TeV: 21.2%

100 TeV: 31.5%

Higgs boson pair invariant mass





for large invariant masses:

Born-improved NLO HEFT overestimates by about 50%, FTapprox by about 40%
(at 14 TeV, worse at 100 TeV)

top quark loops resolved → HEFT has wrong scaling behaviour at high energies

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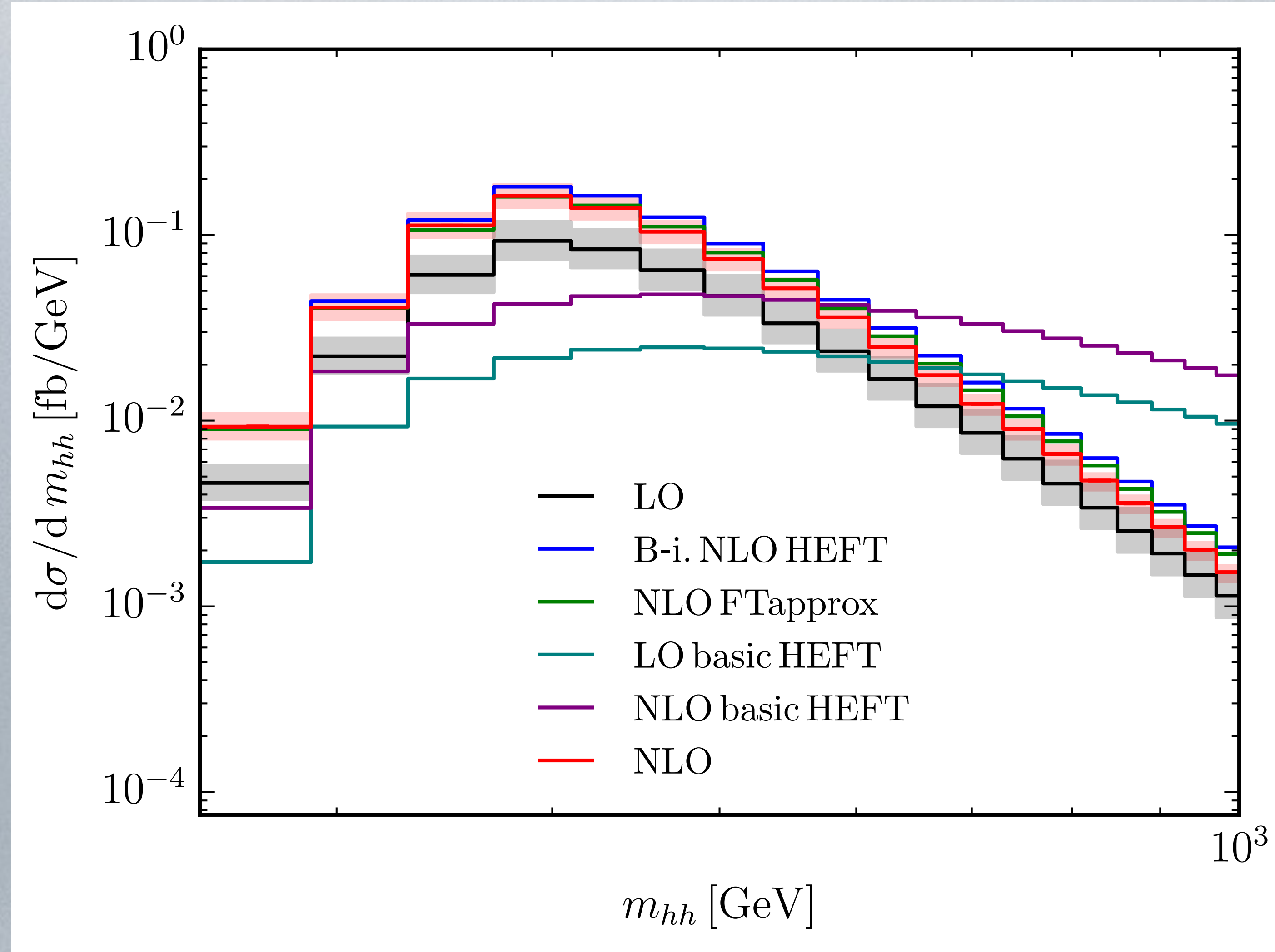
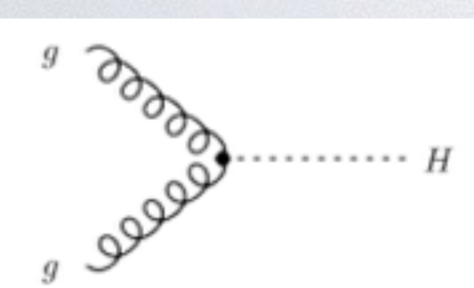
scaling behaviour



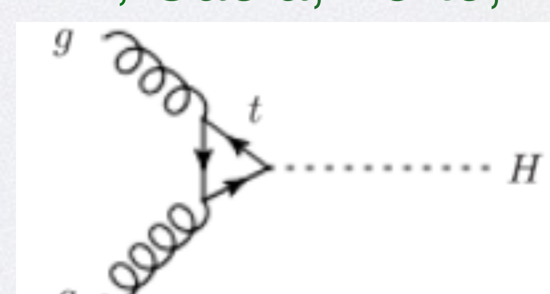
$$\frac{d\hat{\sigma}}{dm_{hh}} \sim m_{hh}^{-3}$$ i.e. partonic cross section scales as $\hat{s}^{-1}$

HEFT approximation: $$\frac{d\hat{\sigma}}{dm_{hh}} \sim m_{hh}$$ i.e. $\hat{\sigma} \sim \hat{s}$

similar for H+jet(s): Greiner, Höche, Luisoni, Schönherr, Winter '16
see also Marzani et al. '08; Caola, Forte, Marzani, Muselli, Vita '16

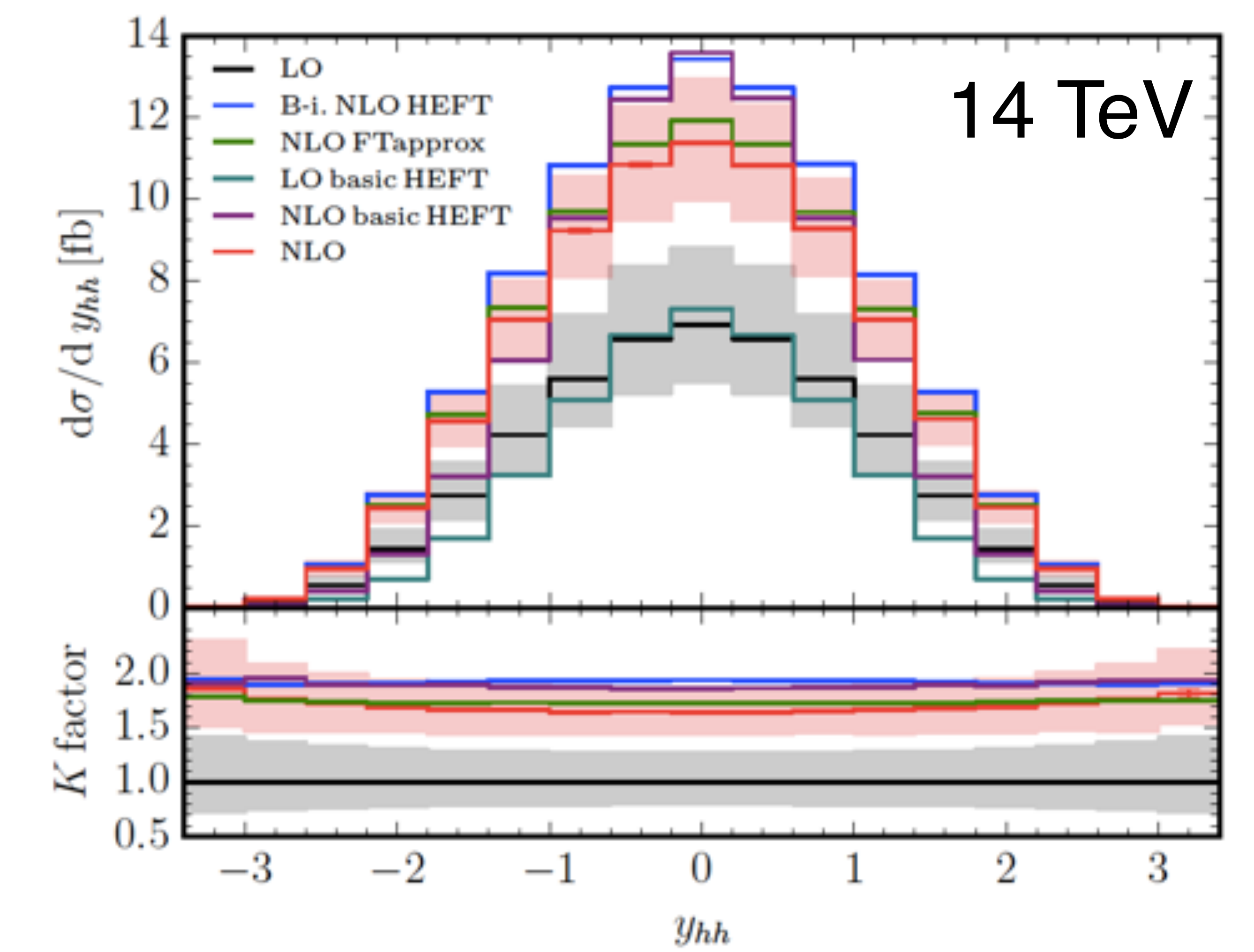


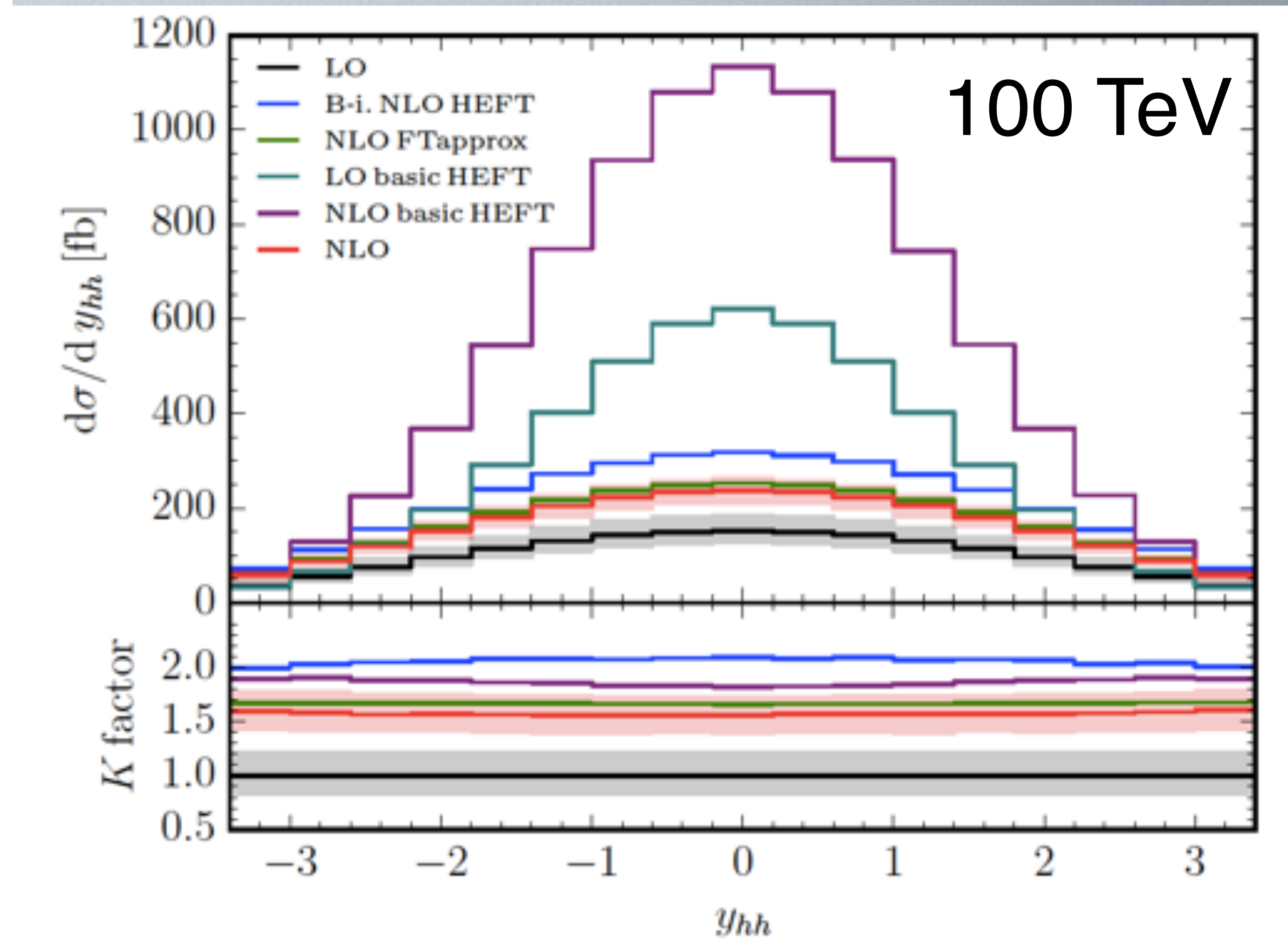
$d\sigma/dp_{T,h}^2 \to (p_{T,h}^2)^{-1}$



$d\sigma/dp_{T,h}^2 \to (p_{T,h}^2)^{-2}$

rapidity of the Higgs boson pair





NLO-improved NNLO HEFT

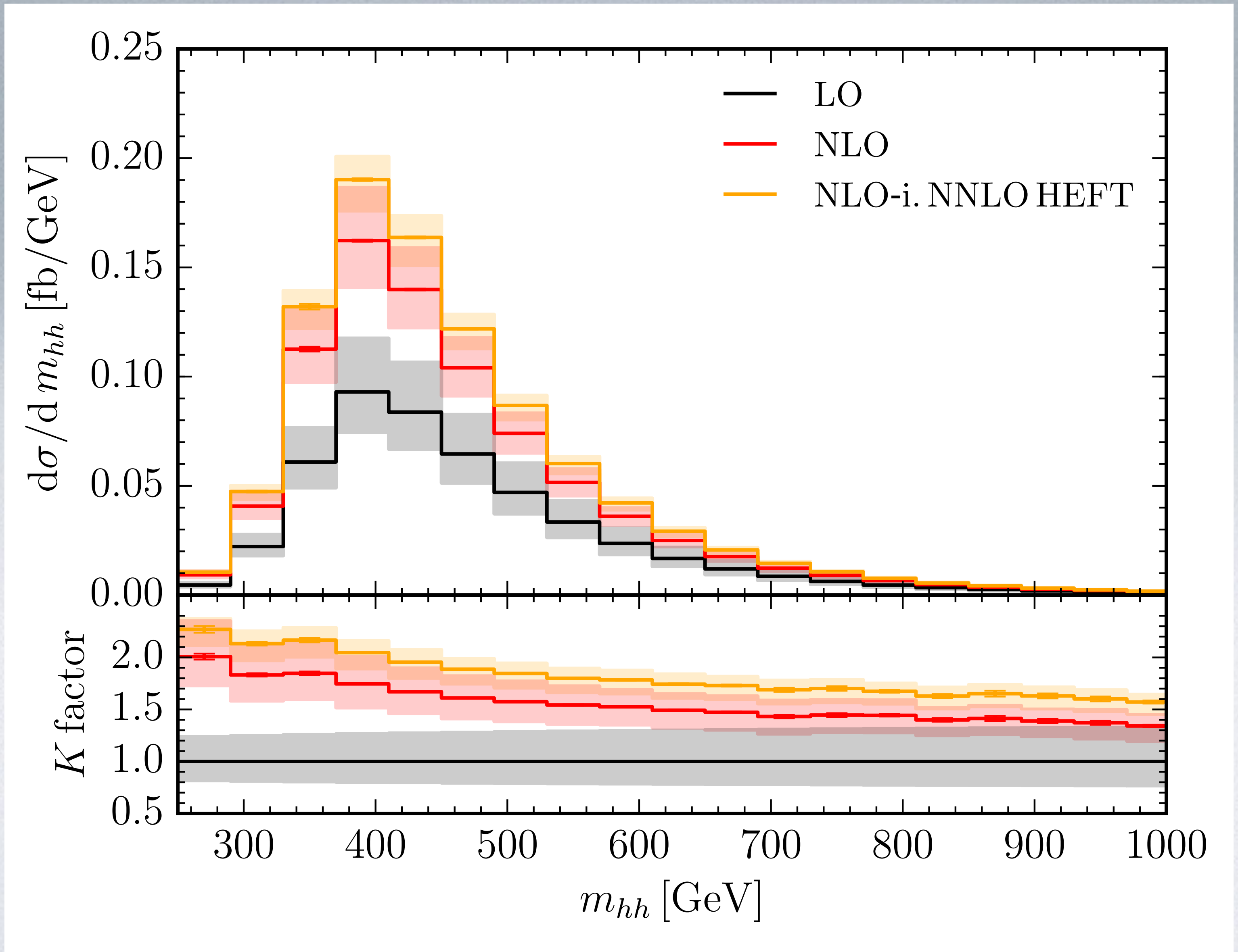
NNLO HEFT:

De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 1606.09519

"NLO-improved NNLO HEFT": [Borowka, Greiner, GH, Jones, Kerner, Schlenk, Zirke 1608.04798]

$$\frac{d\sigma^{\mathrm{NLO-i.NNLO\,HEFT}}}{dm_{hh}} = \frac{d\sigma_{\mathrm{NLO}}}{dm_{hh}} \times \frac{d\sigma^{\mathrm{HEFT}}_{\mathrm{NNLO}}/dm_{hh}}{d\sigma^{\mathrm{HEFT}}_{\mathrm{NLO}}/dm_{hh}}$$

bin-by-bin rescaling at observable level by NNLO HEFT K-factor



would lead to

$\sigma' = 38.56\ fb$

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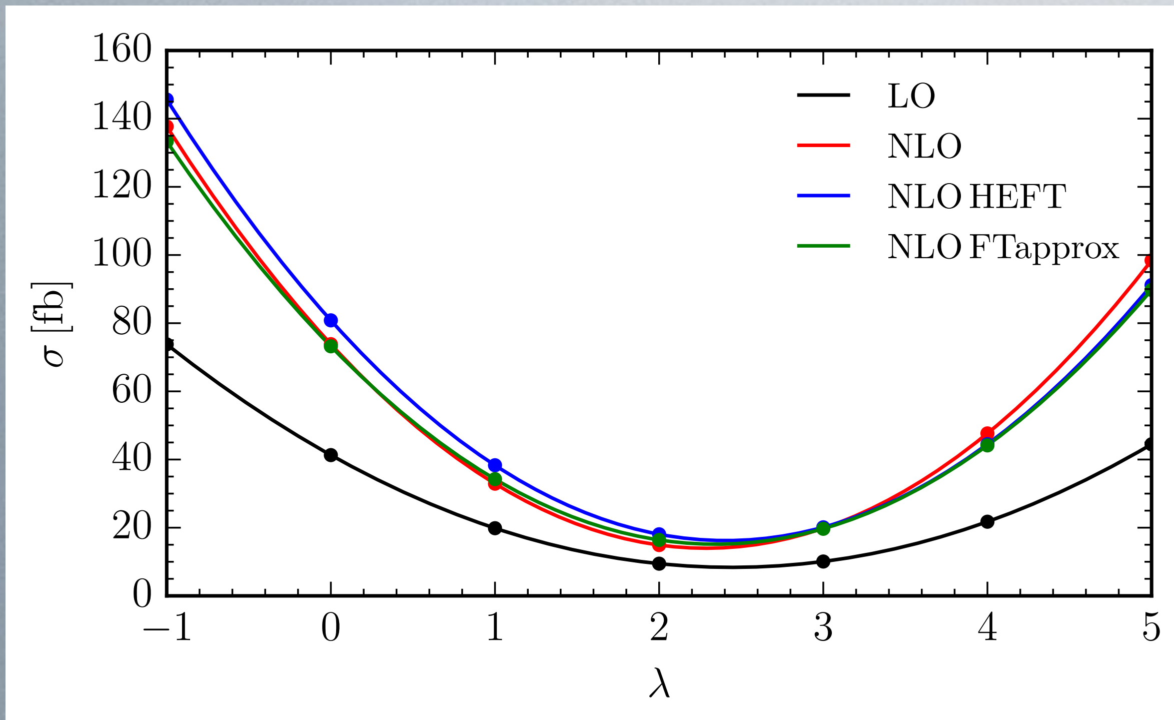
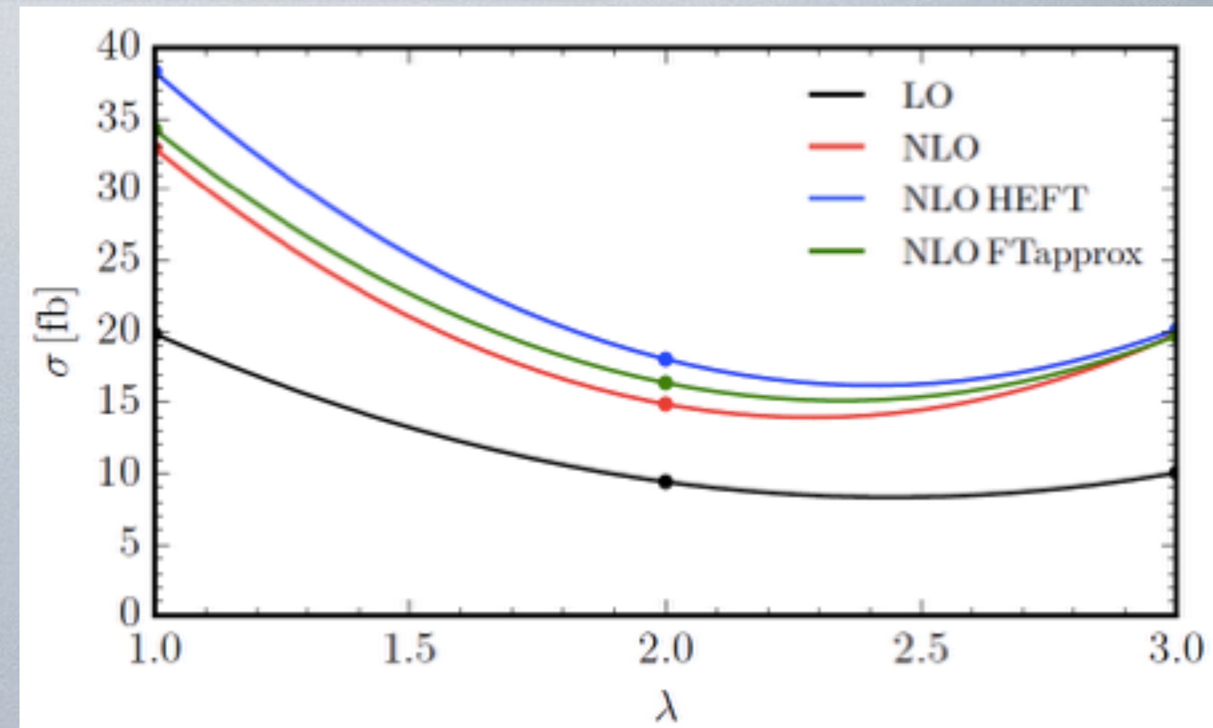
variation of triple Higgs coupling

$$\lambda = \lambda_{BSM}/\lambda_{SM}$$

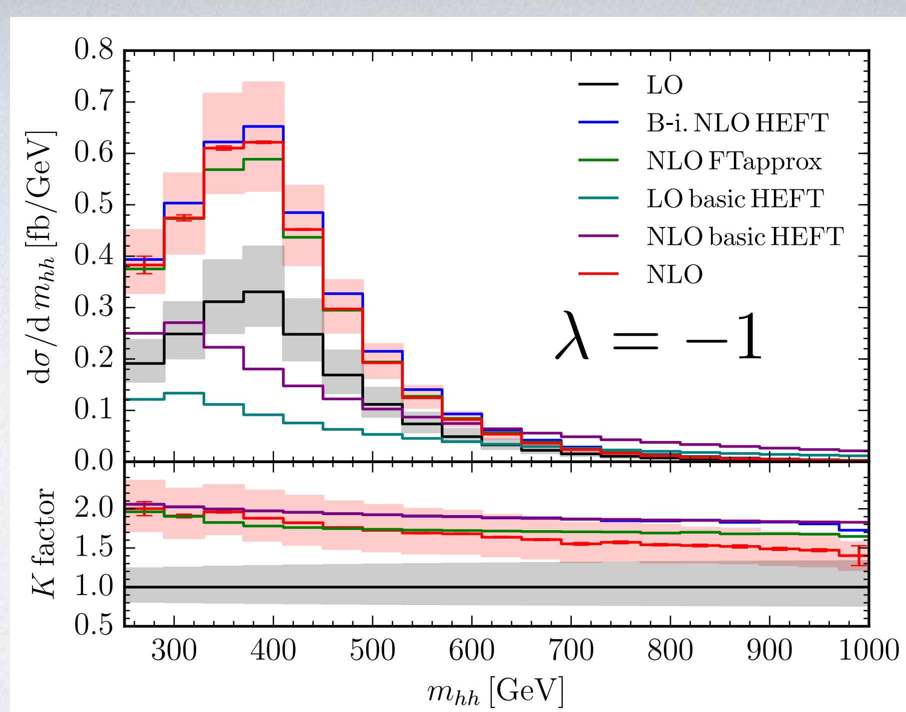


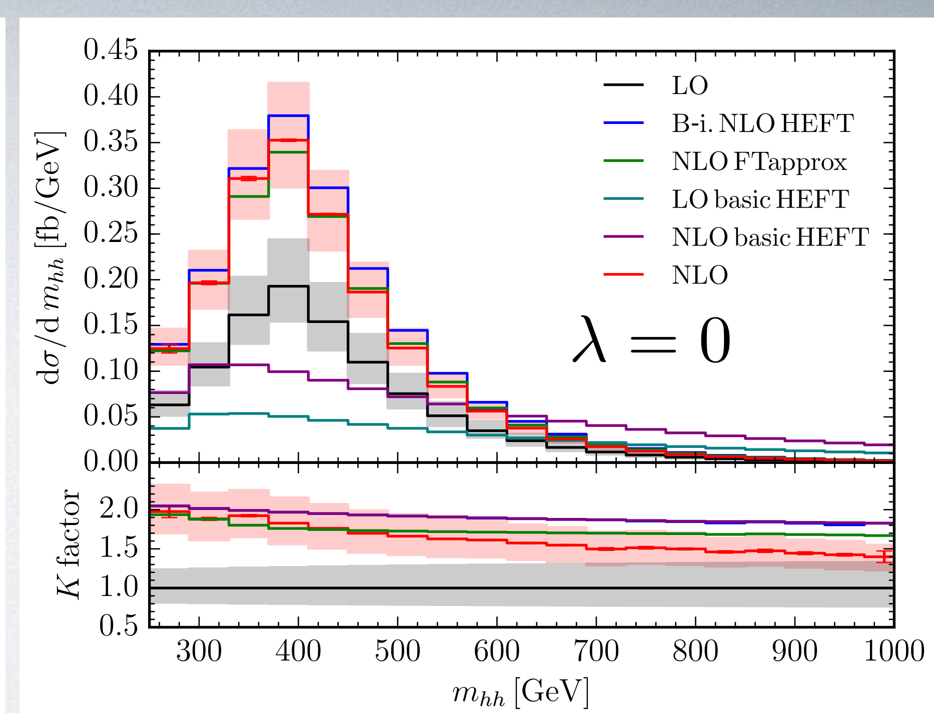


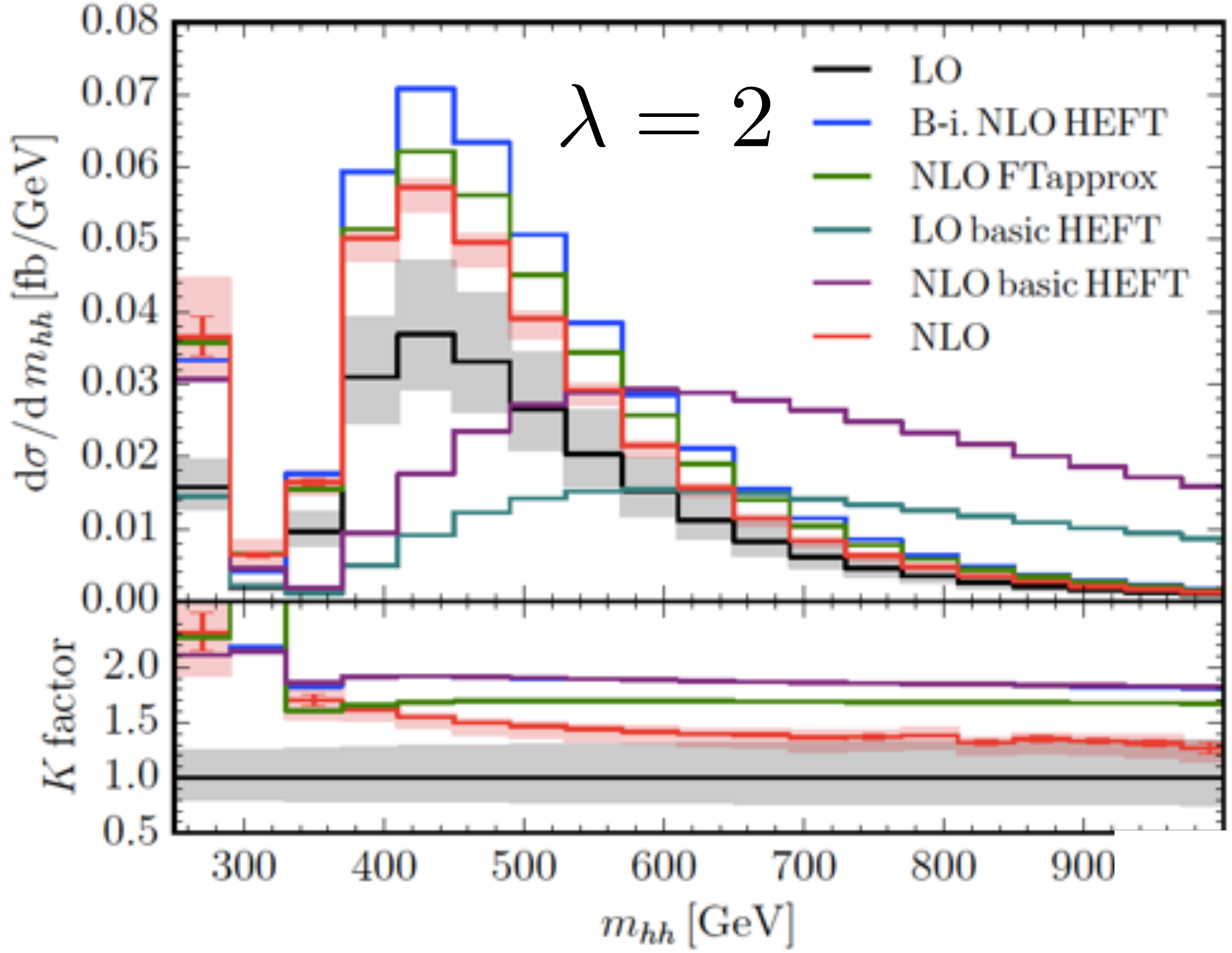
minimum near $\lambda = 2$ due to **destructive interference** between diagrams containing λ and box-type diagrams

degeneracy due to quadratic λ dependence

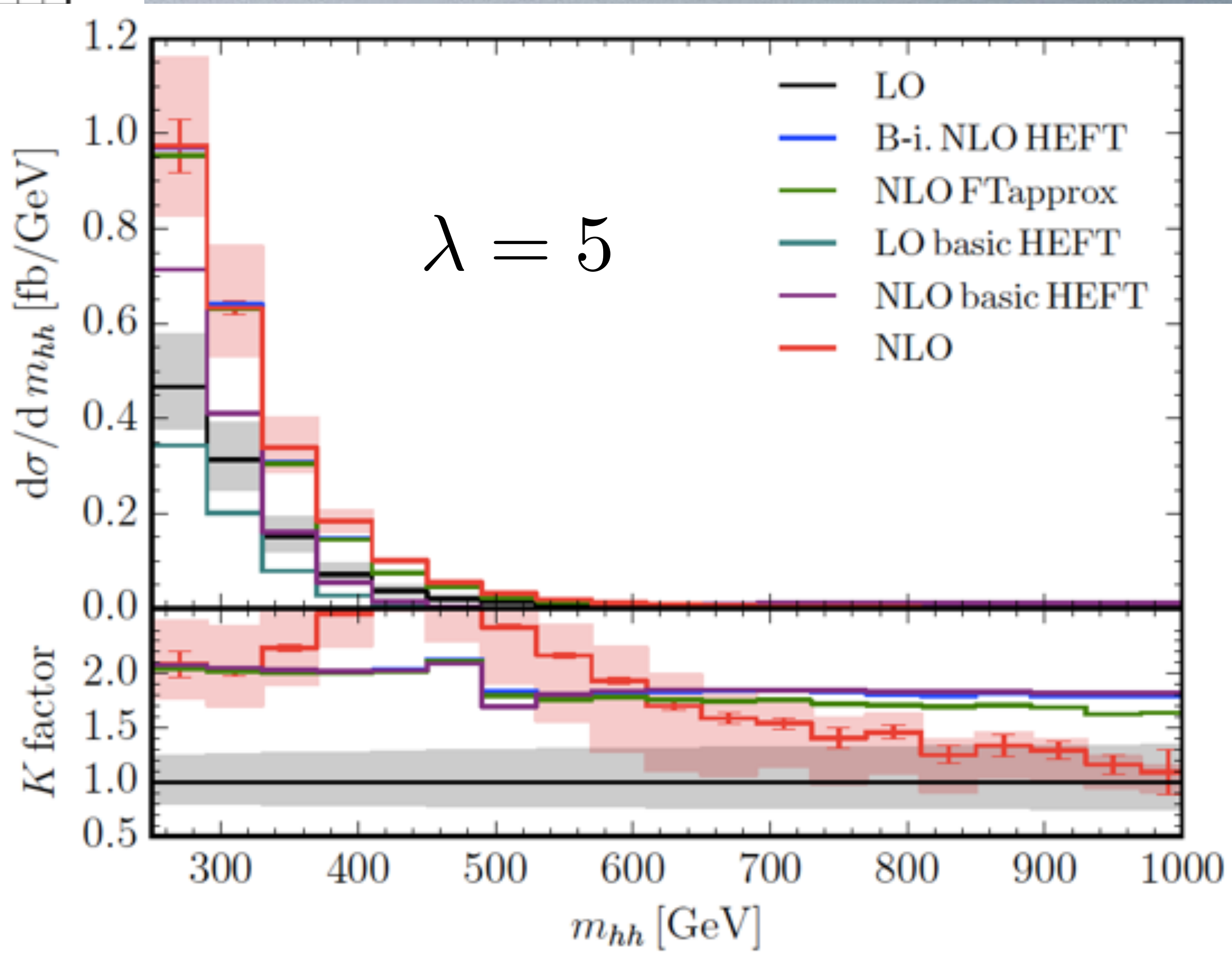
distributions can discriminate between degenerate λ values





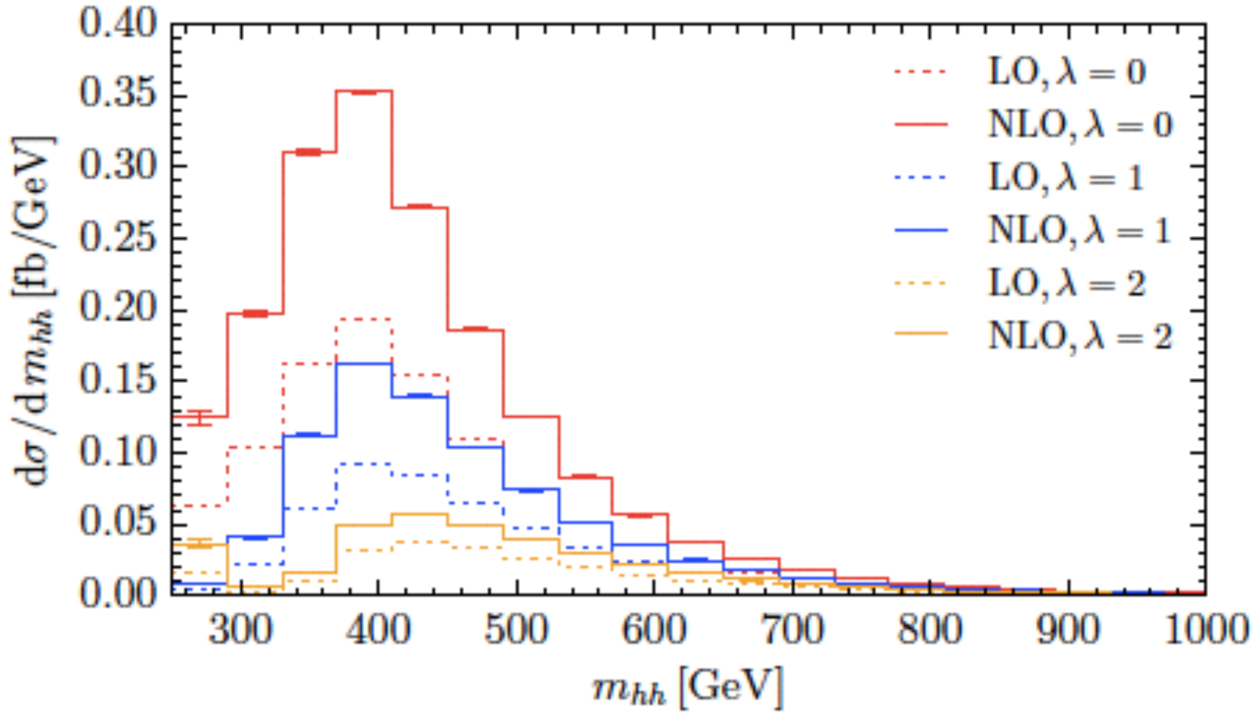


λ = 2
LO
B-i. NLO HEFT
NLO FTapprox
LO basic HEFT
NLO basic HEFT
NLO
dσ/d m_hh [fb/GeV]
K factor
m_hh [GeV]

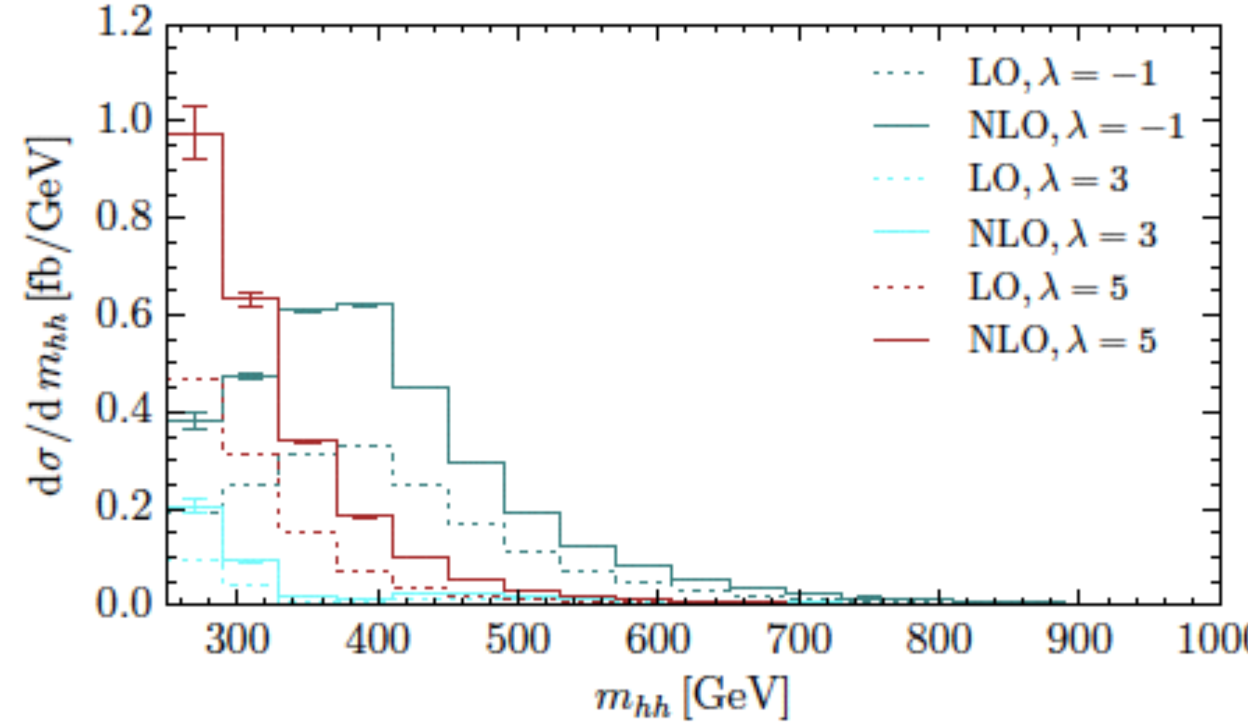


λ = 5
LO
B-i. NLO HEFT
NLO FTapprox
LO basic HEFT
NLO basic HEFT
NLO
dσ/d m_hh [fb/GeV]
K factor
m_hh [GeV]

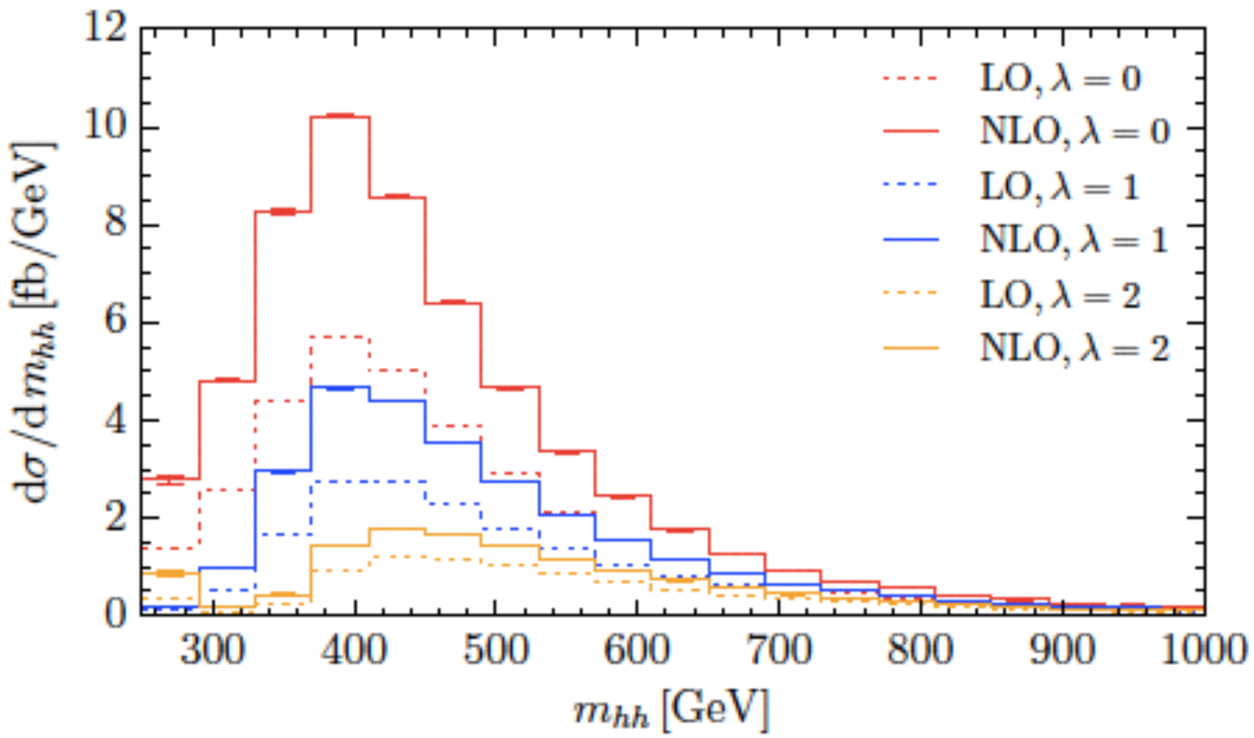
variation of triple Higgs coupling



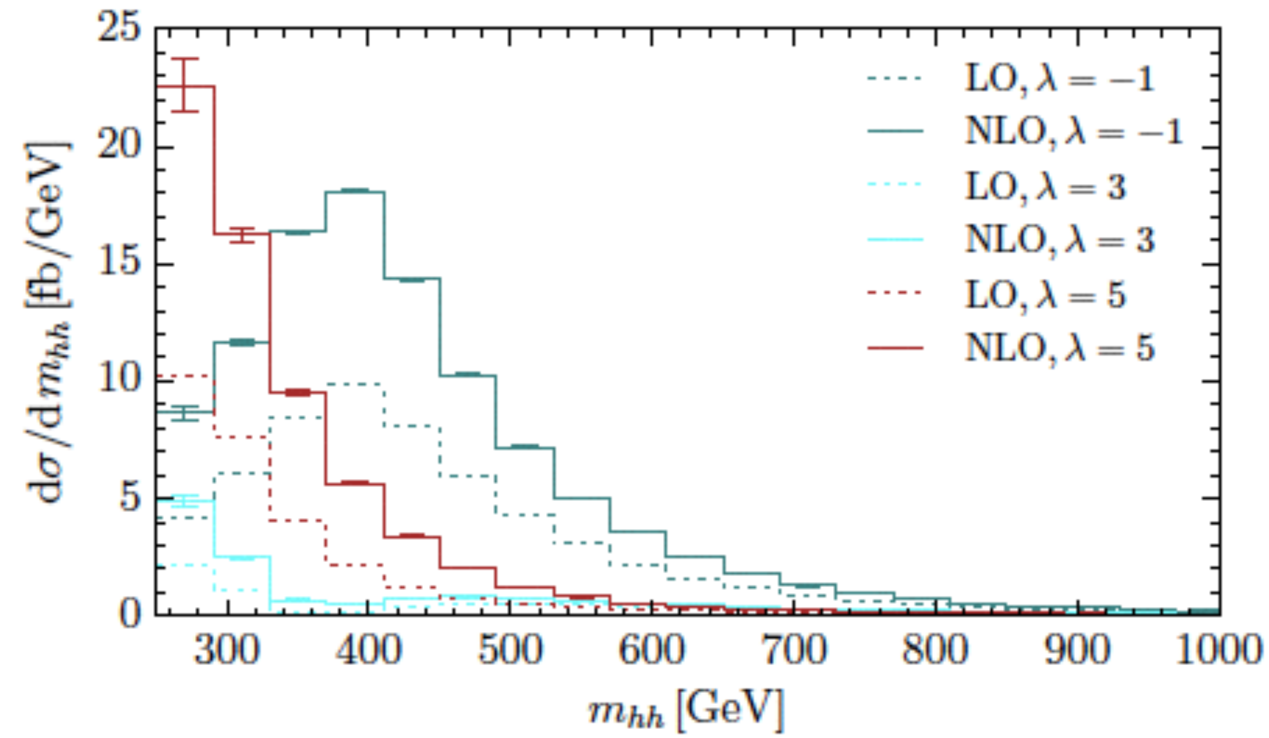
(a) 14 TeV.



(b) 14 TeV.



(c) 100 TeV.



(d) 100 TeV.

combination with parton showers

GH, S.Jones, M.Kerner, G.Luisoni, E.Vryonidou '17

- avoid evaluation of two-loop amplitude for each phase space point
- two-loop amplitude depends only on $\hat{s}, \hat{t} \quad (m_t, m_H \text{ fixed})$

  → construct 2-dim grid

- variable transformation to achieve more uniform distribution

$$x = f(\beta(\hat{s})), \quad c_\theta = |\cos\theta| = \left|\frac{\hat{s} + 2\hat{t} - 2m_H^2}{\hat{s}\beta(\hat{s})}\right| \qquad \beta(\hat{s}) = \sqrt{1 - 4m_H^2/\hat{s}}$$

combination with POWHEG and MadGraph5_aMC@NLO

POWHEG-BOX-V2: User-Process-V2/ggHH

and Sherpa S. Jones, S. Kuttimalai '17

combination with parton showers

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- two-loop amplitude depends only on $\hat{s}, \hat{t}$ $\quad (m_t, m_H \text{ fixed})$

  → construct 2-dim grid

- variable transformation to achieve more uniform distribution

$$x = f(\beta(\hat{s})), \quad c_\theta = |\cos\theta| = \left| \frac{\hat{s} + 2\hat{t} - 2m_H^2}{\hat{s}\beta(\hat{s})} \right| \qquad \beta(\hat{s}) = \sqrt{1 - 4m_H^2/\hat{s}}$$

combination with POWHEG and MadGraph5_aMC@NLO

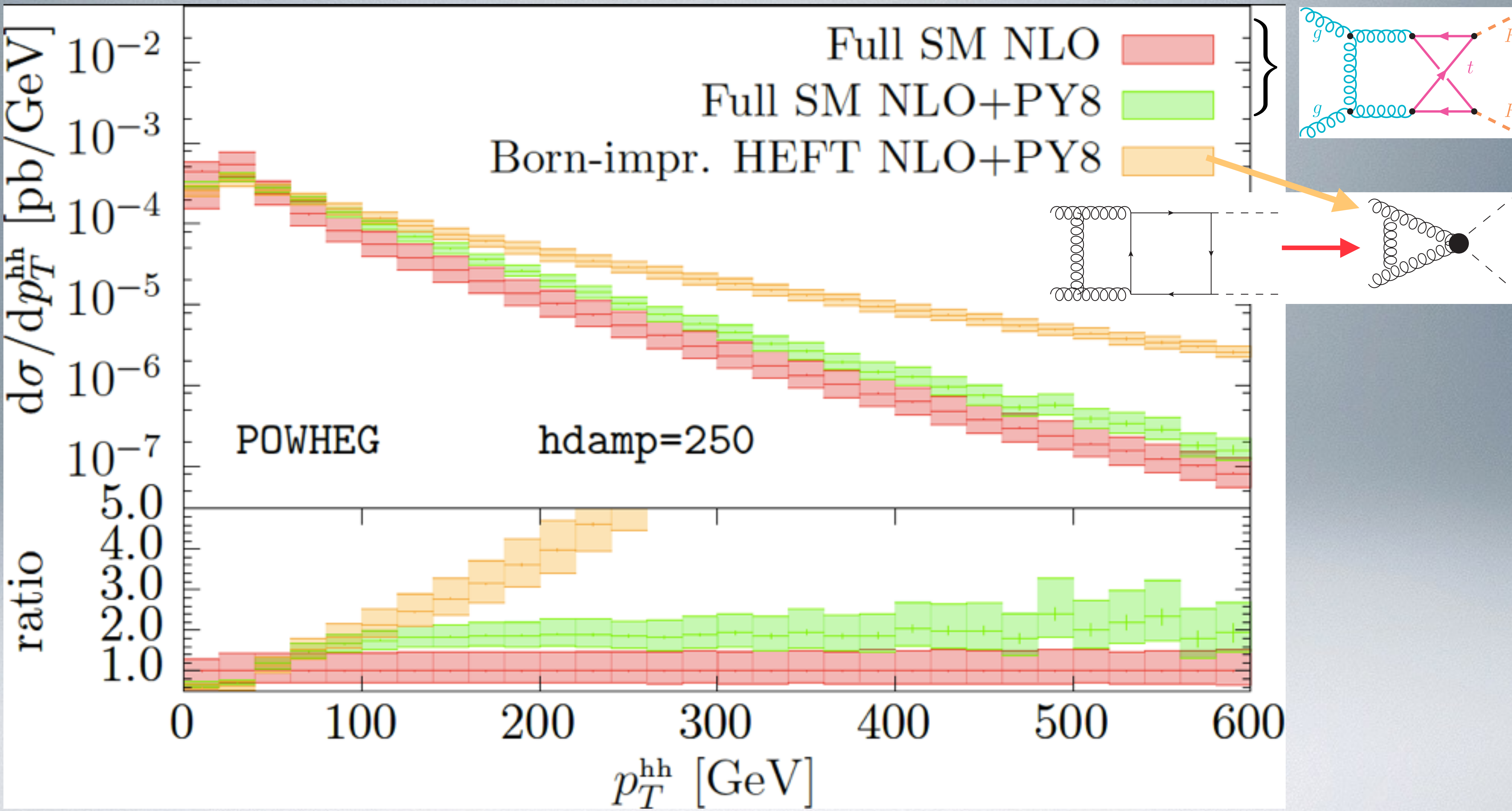
POWHEG-BOX-V2: User-Process-V2/ggHH

public

and Sherpa S. Jones, S. Kuttimalai '17

mass effects versus parton shower effects

GH, S.Jones, M.Kerner, G.Luisoni, E.Vryonidou 1703.09252



mass effects versus parton shower effects

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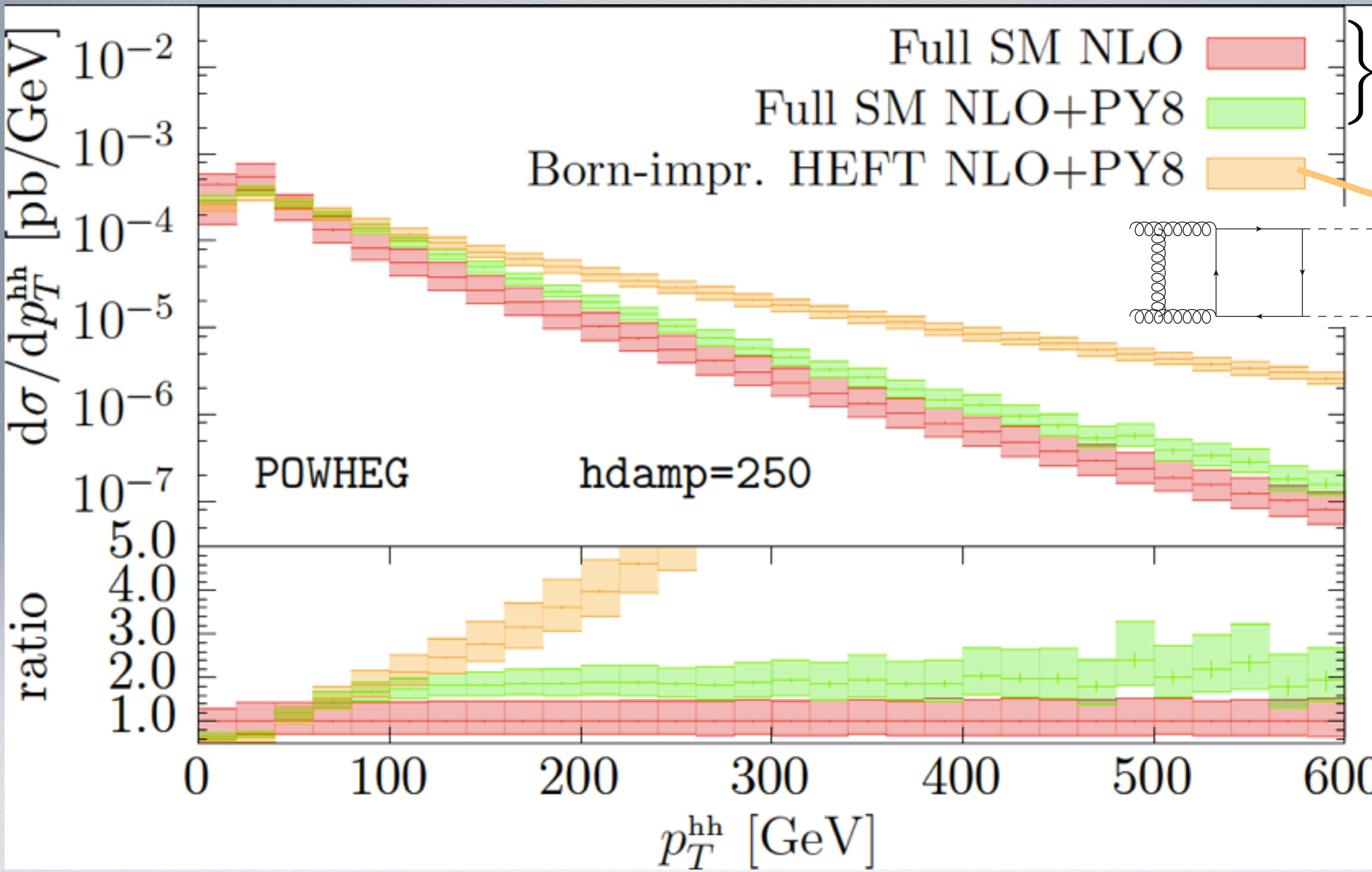
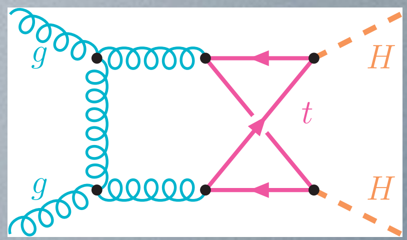
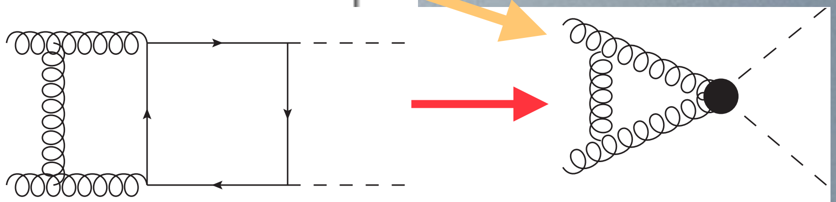
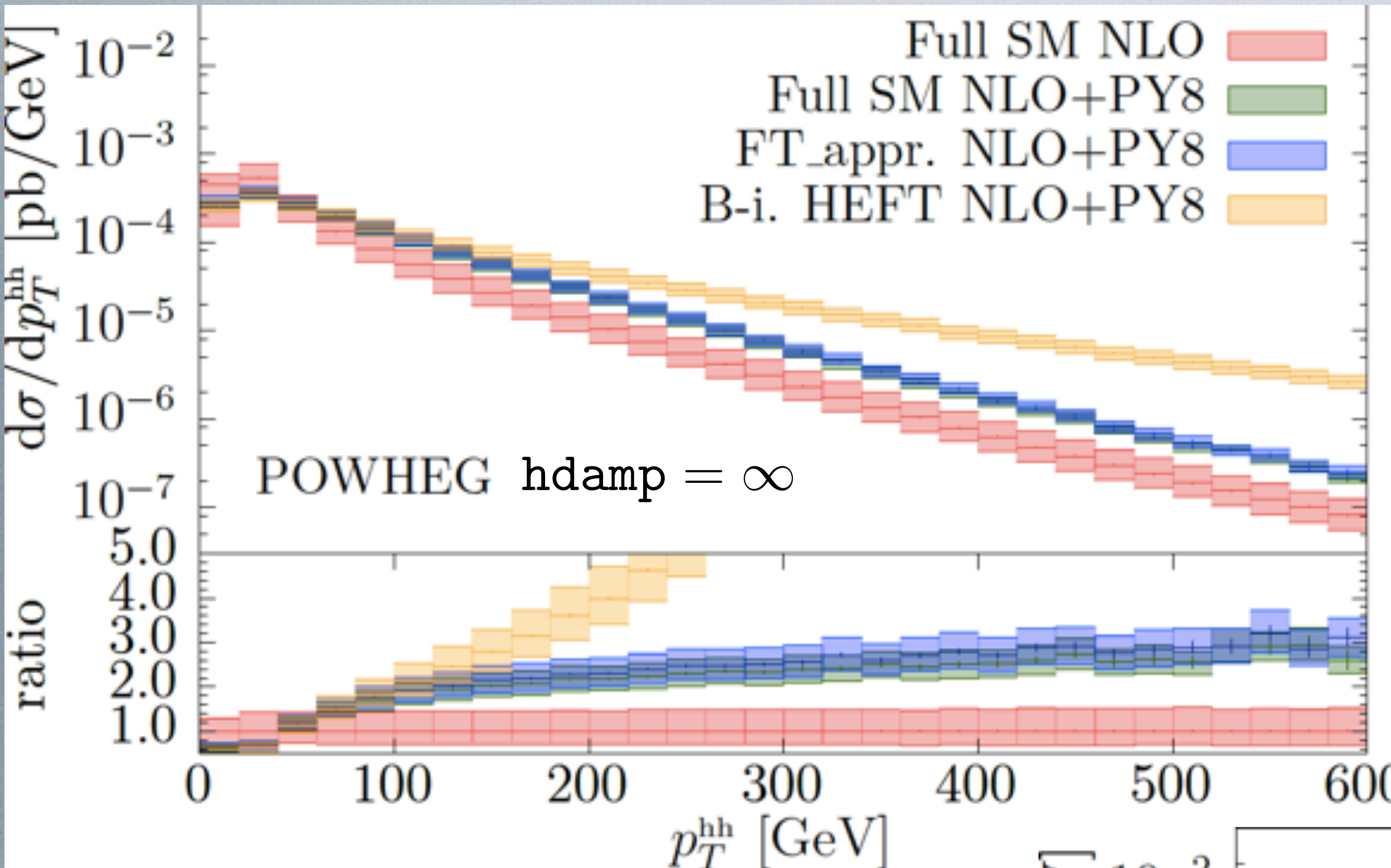






shower effects large but order(s) of magnitude smaller than difference to Born-improved HEFT

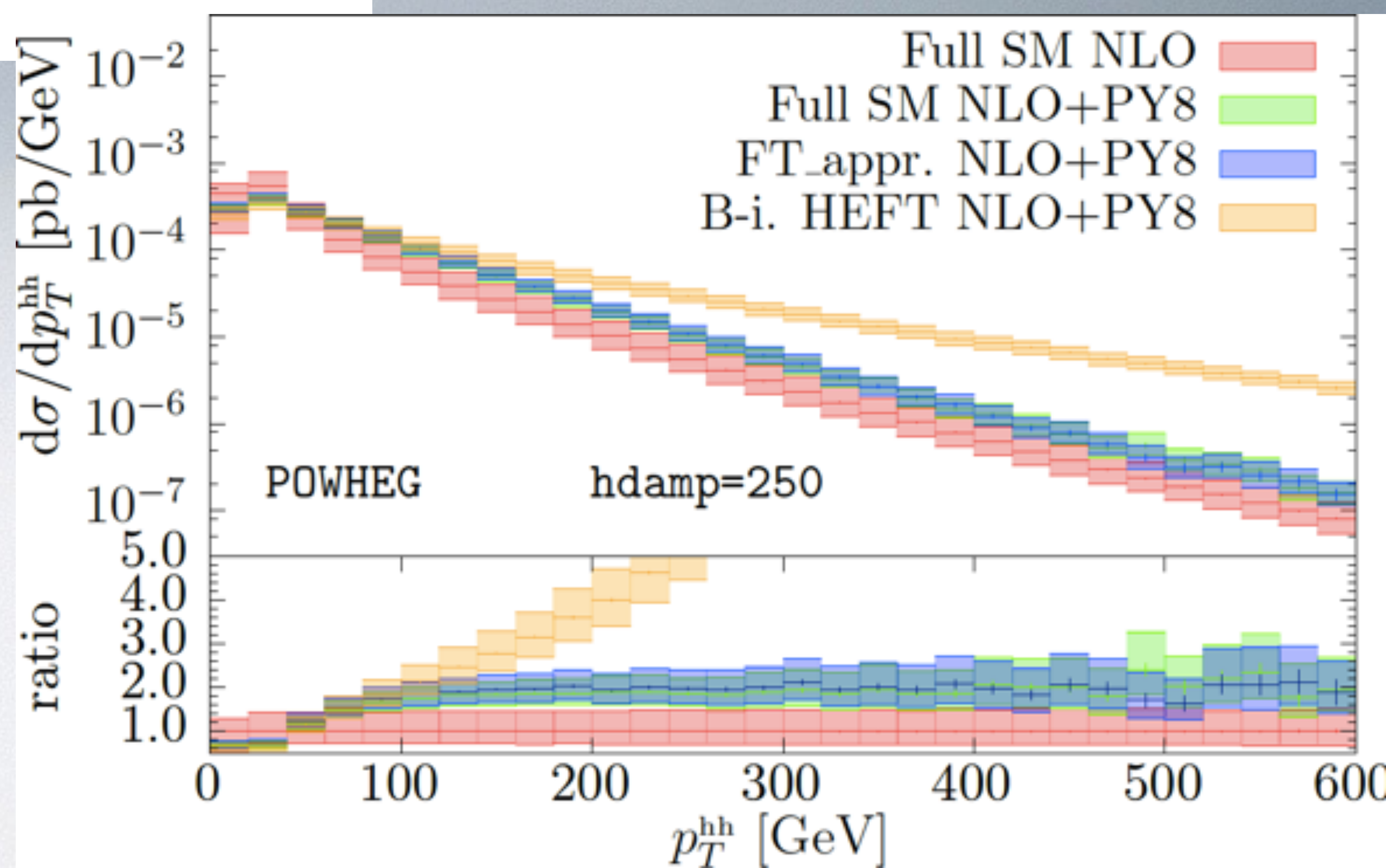
dependence on shower parameters



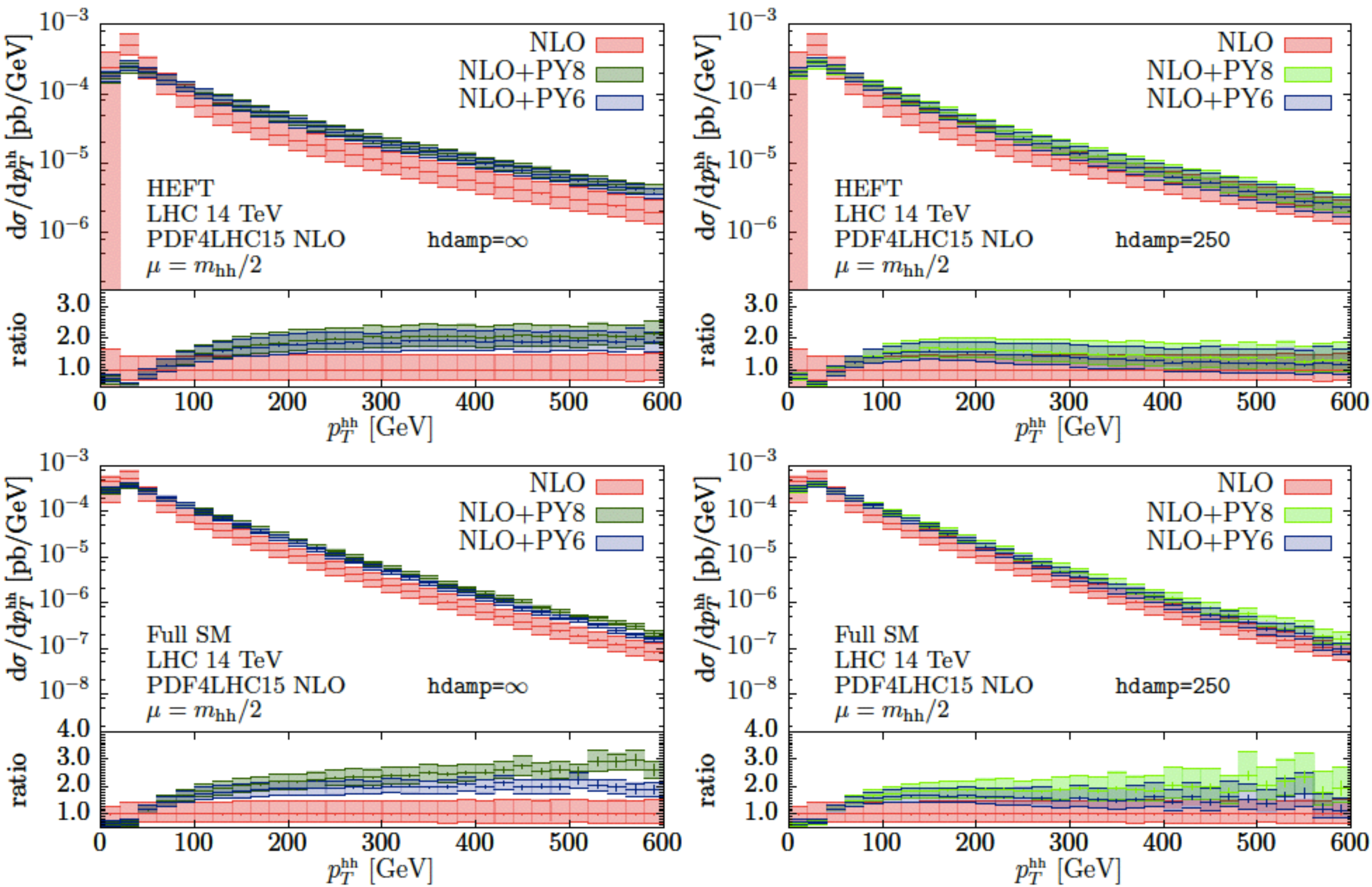
hdamp=h limits amount of exponentiated hard radiation

$$R_{\text{sing}} = R \times F\,,$$
$$R_{\text{reg}} = R \times (1 - F)$$

$$F = \frac{h^2}{(p_T^{\text{hh}})^2 + h^2}$$

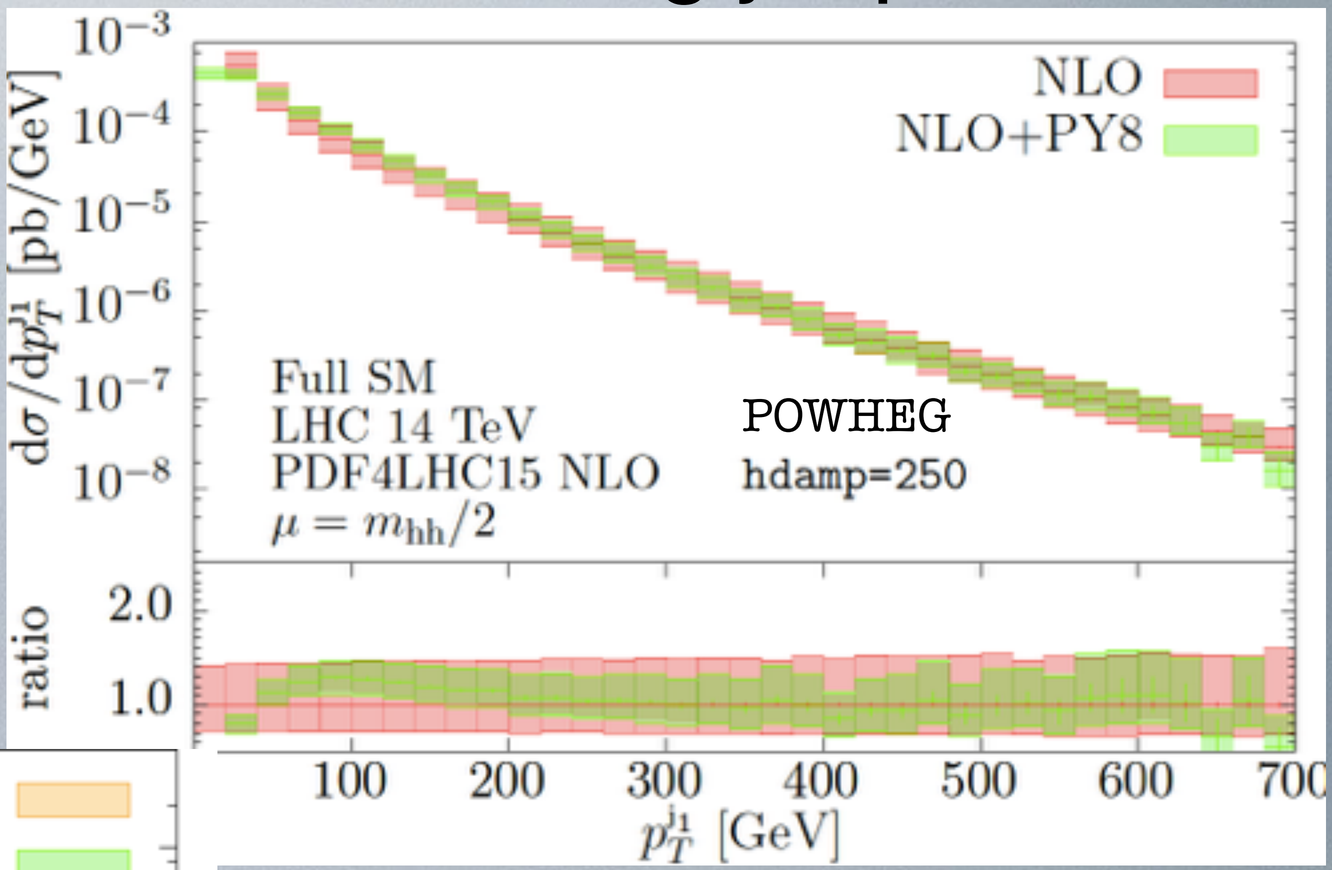


compare Pythia6 and Pythia8

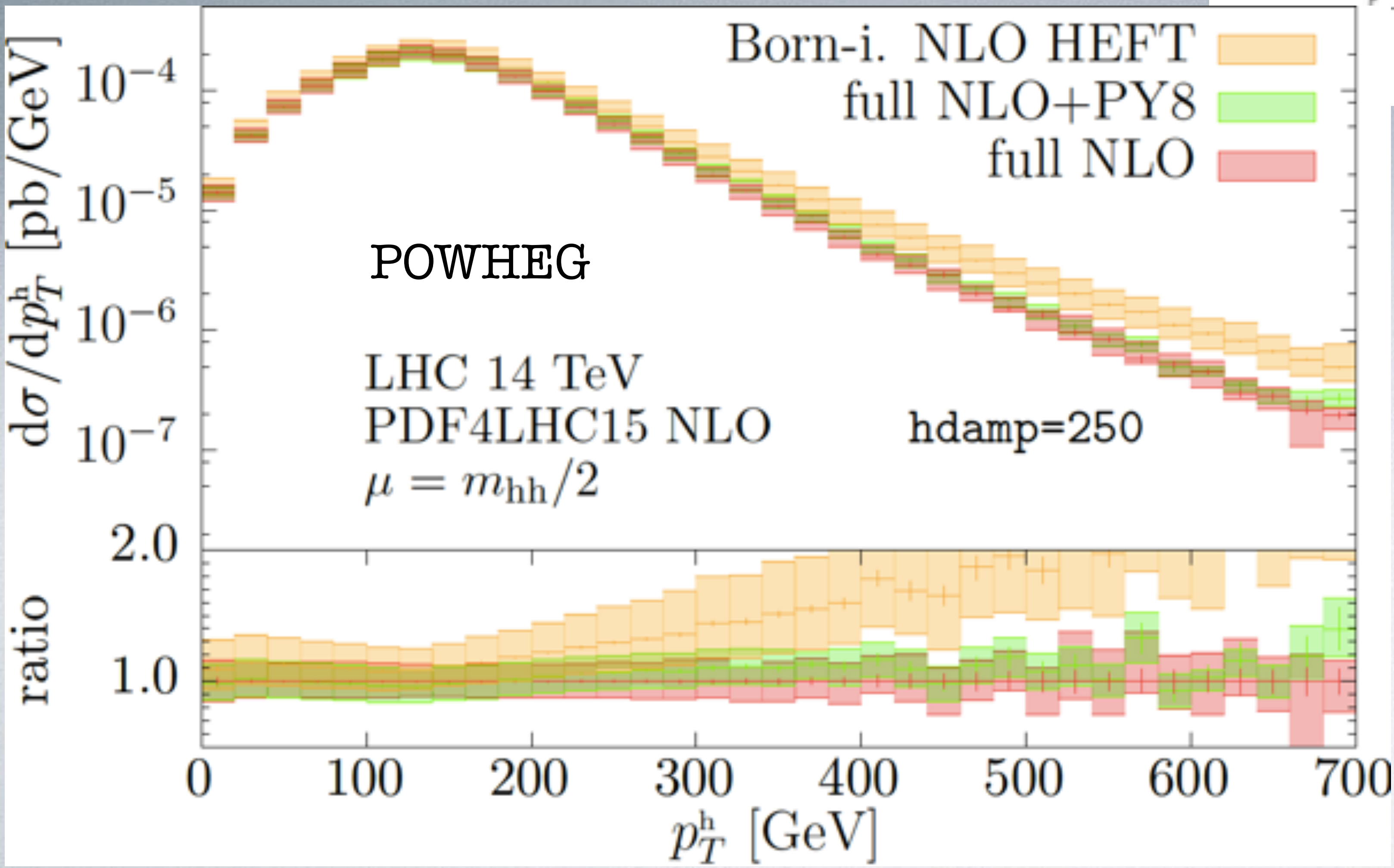


other observables

leading jet pT

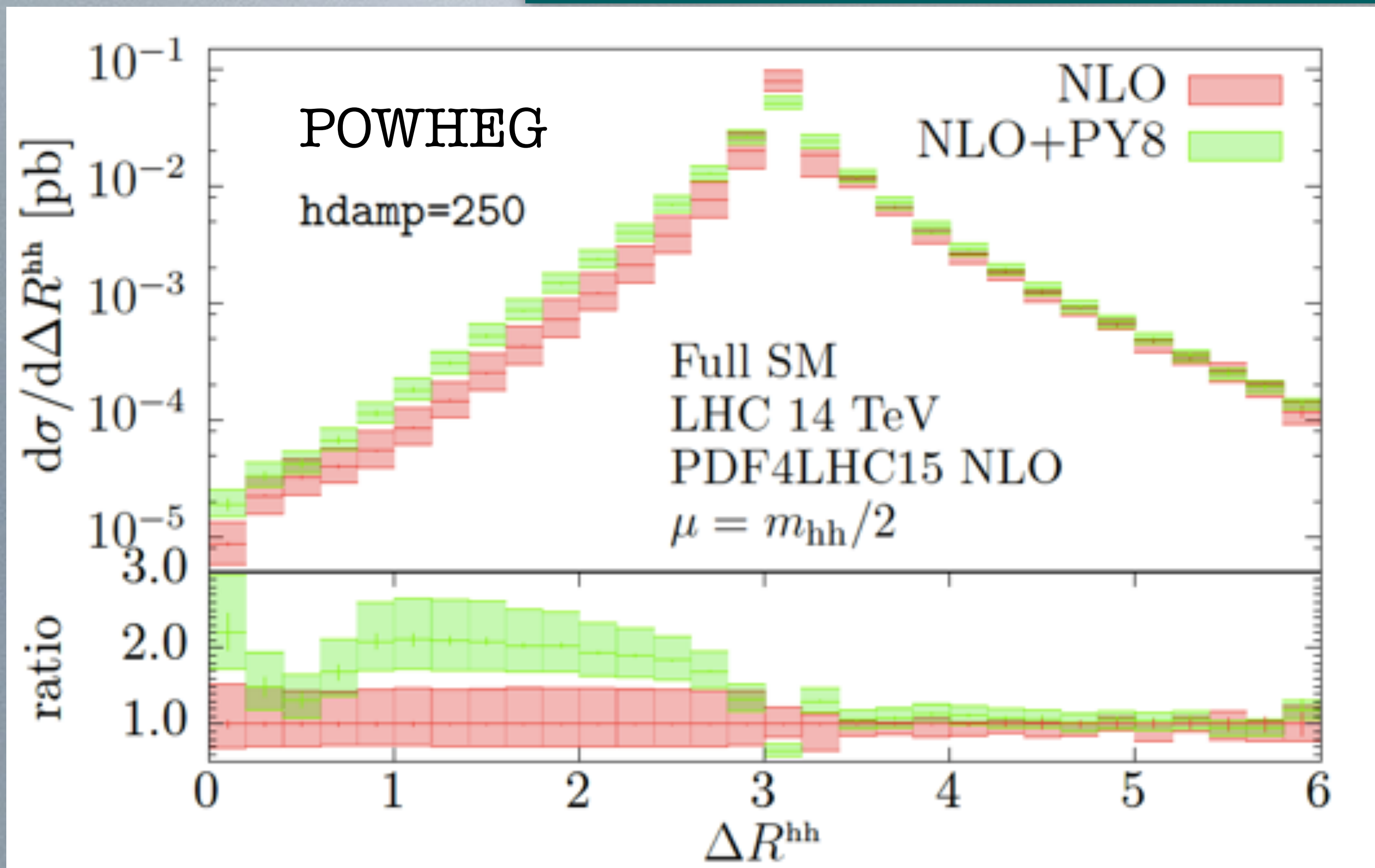


pT of one Higgs boson



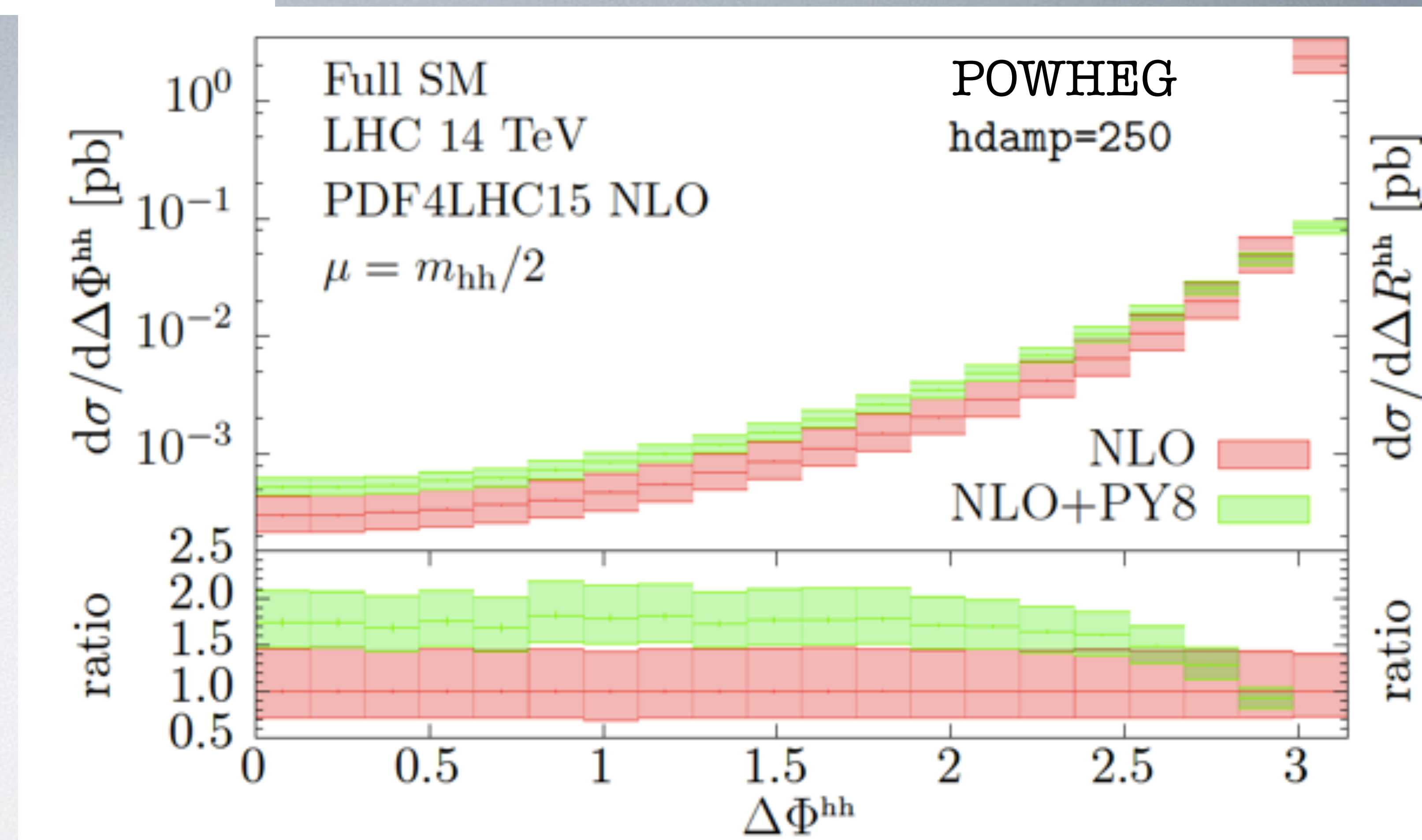
Born-improved HEFT:
reweighting at event level

compare fixed order and showered results



$$\Delta R^{hh} = \sqrt{(\eta_1 - \eta_2)^2 + (\Phi_1 - \Phi_2)^2}$$

for $\Delta R^{hh} < \pi$ fixed order is only "LO accurate"



MAX-PLANCK-GESELLSCHAFT

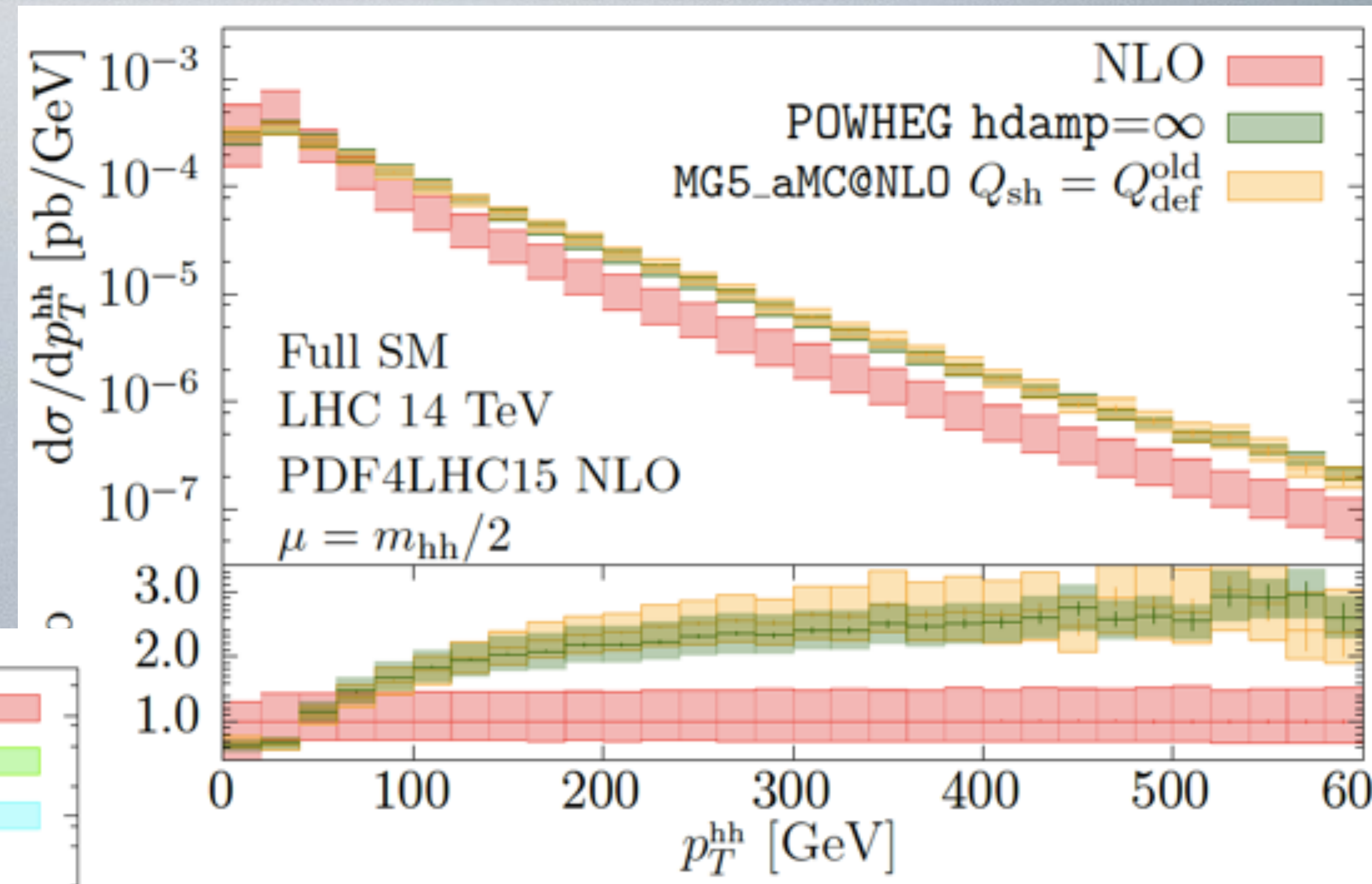
compare POWHEG and MG5_aMC@NLO

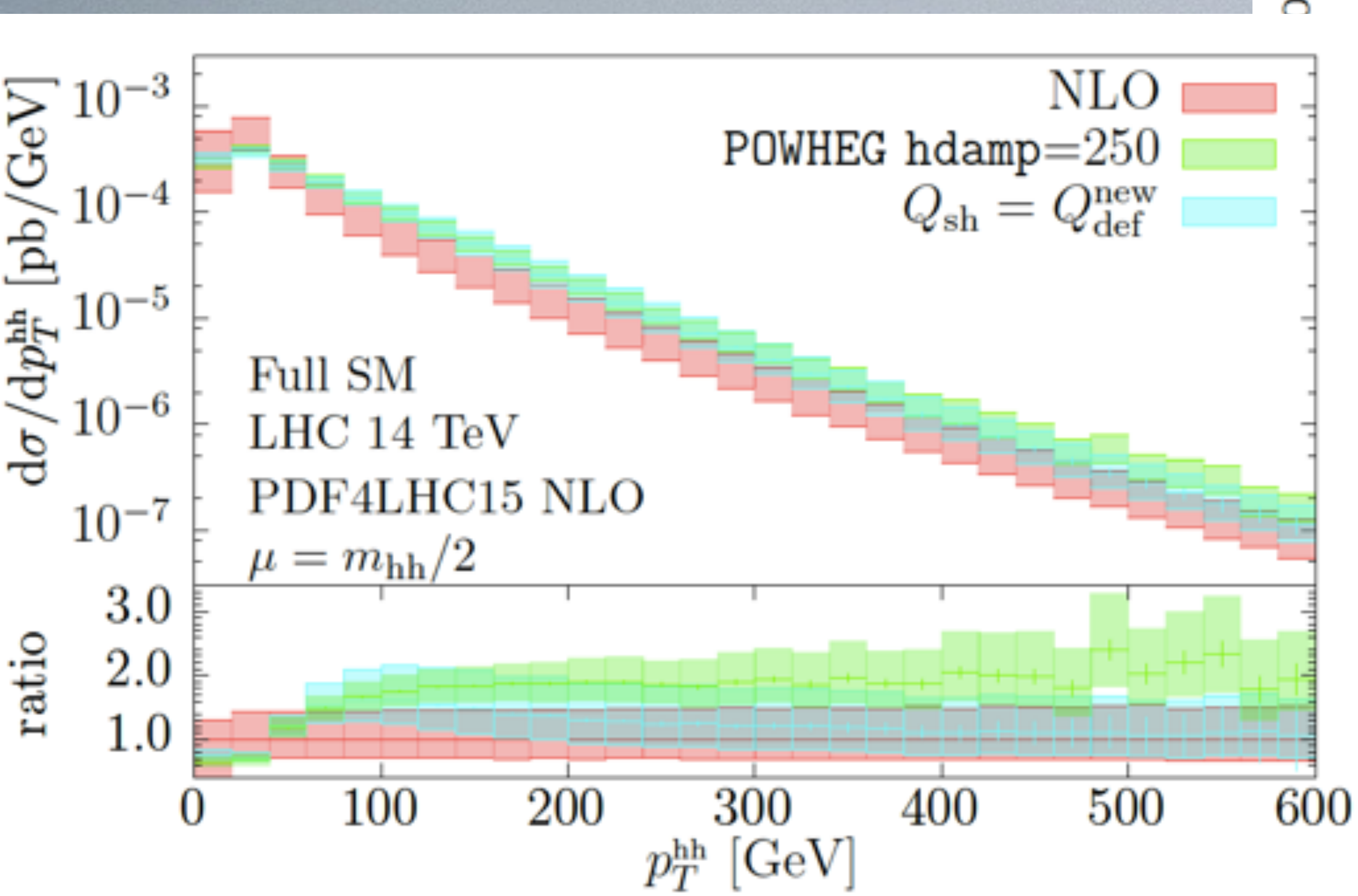
MG5_aMC@NLO version 2.5.3:

new `Qsh`

picked with some probability distribution in

$\texttt{shower\_scale\_factor} \times [0.1\, H_T/2, H_T/2]$





MG5_aMC@NLO
old shower starting scale `Qsh`:

picked with some probability distribution in

$\texttt{shower\_scale\_factor} \times [0.1\sqrt{\hat{s}}, \sqrt{\hat{s}}]$

new default shower starting scale matches onto NLO fixed order at large `pThh`

combination with Sherpa

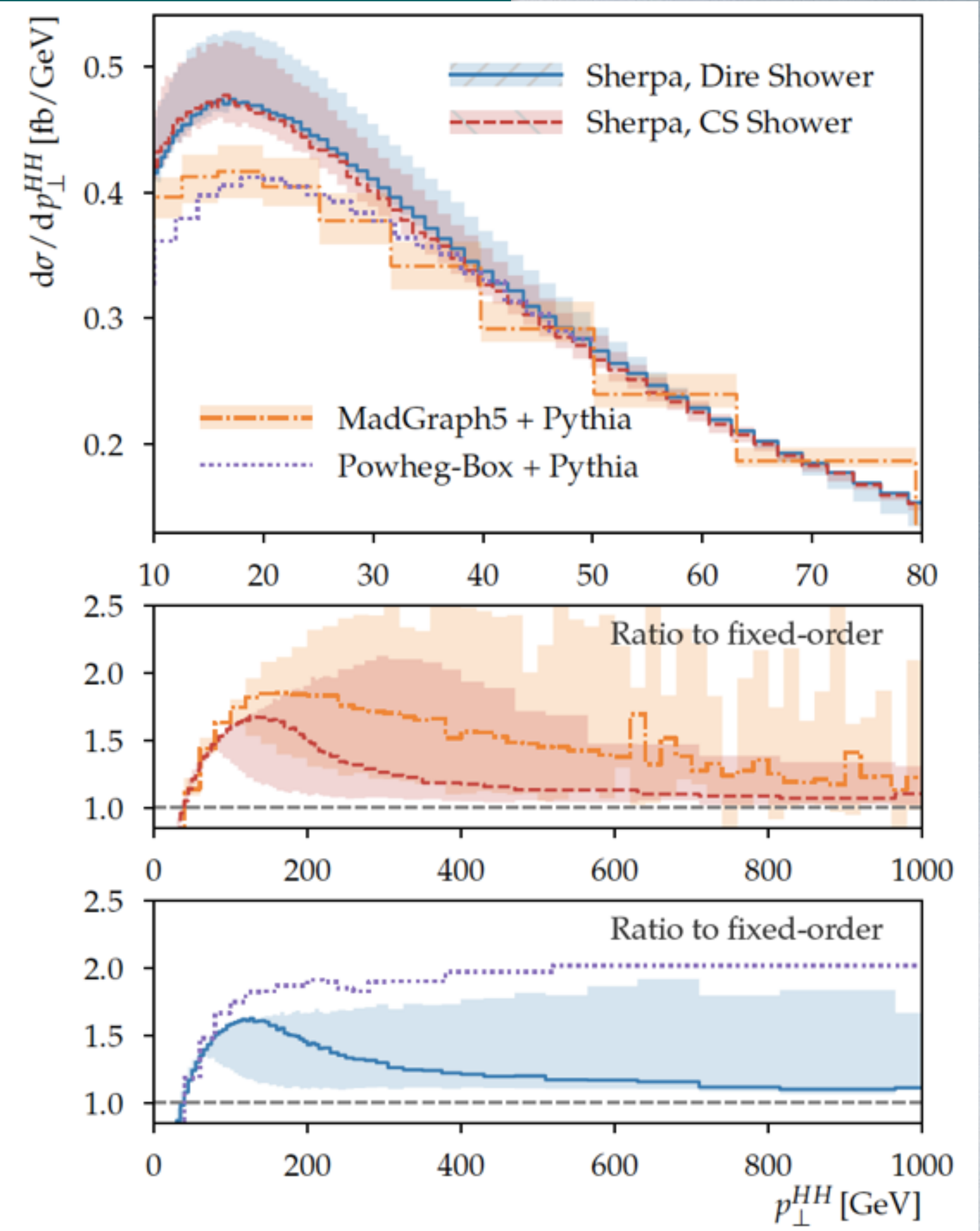
S. Jones,
S. Kuttimalai ‘17

- differences in peak region due to different matching algorithms

- large pTHH region:

MG5_aMC@NLO results within (large) uncertainty bands

Powheg with hdamp=250 not within μ_{PS} variation band; vary hdamp to obtain Powheg uncertainty band

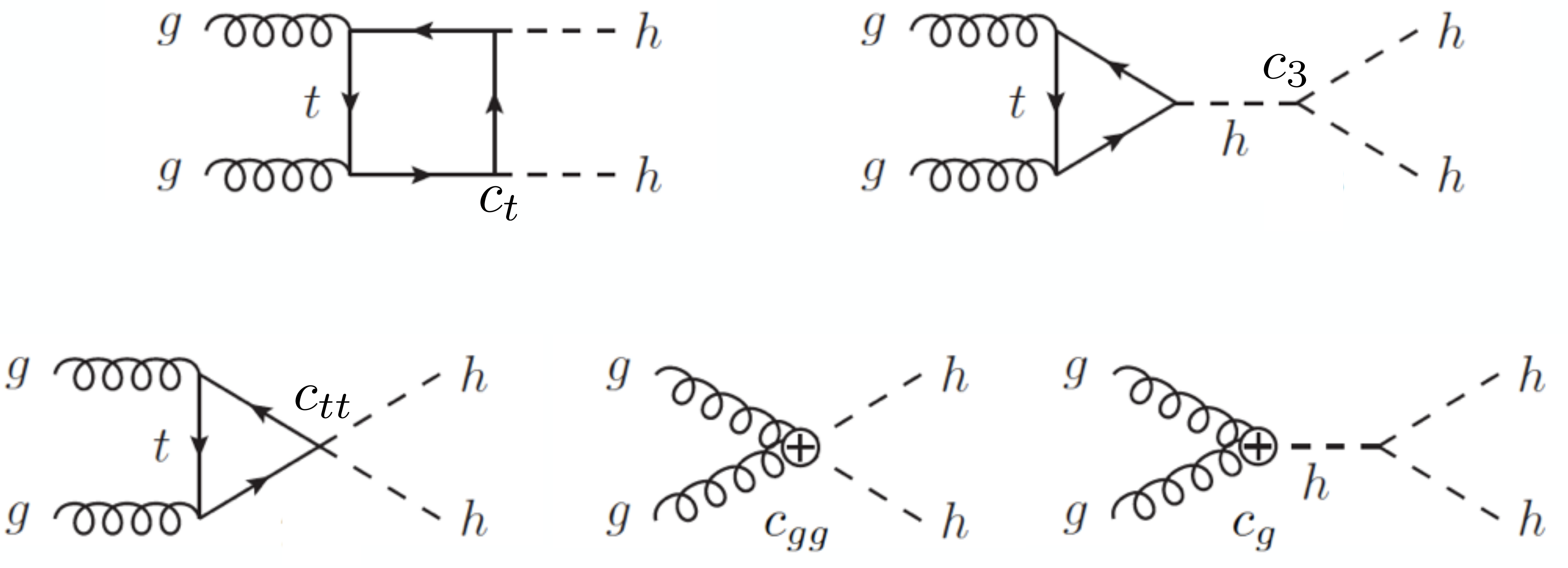


BSM couplings

effective Lagrangian: see e.g. Contino et al. '10, Buchalla et al. '13

$$\Delta\mathcal{L}_{\text{non-lin}} \supset -m_t\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{2v^2}\right)-c_3\frac{1}{6}\left(\frac{3M_h^2}{v}\right)h^3+\frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{2v^2}\right)$$

5 modified/BSM couplings



BSM couplings

Gröber, Mühlleitner, Spira, Streicher ’15:

calculated effects of dimension 6 operators in Born-improved HEFT

our plan: (Buchalla, Capozi, Celis, GH, Scyboz et al)

calculate effects of BSM couplings based non-linear effective Lagrangian with full top quark mass dependence

use benchmark points of
Carvalho, Dall’Osso, Dorigo, Goetz, Gottardo, Tosi ‘15

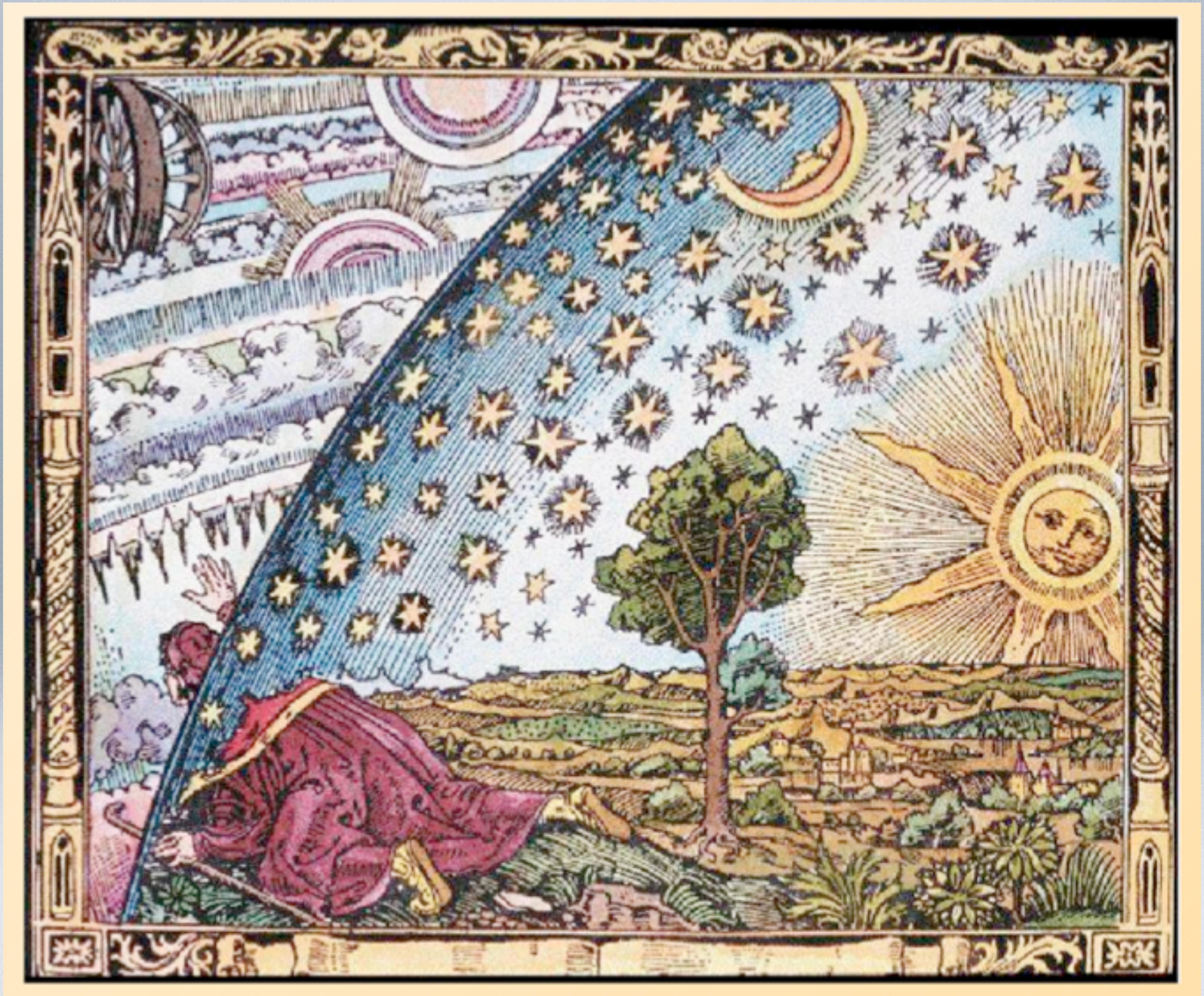
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

Summary & outlook

- Born-improved HEFT approximation fails to describe tails of distributions
- discrepancy grows with energy
- at high energies mass effects more important than shower effects

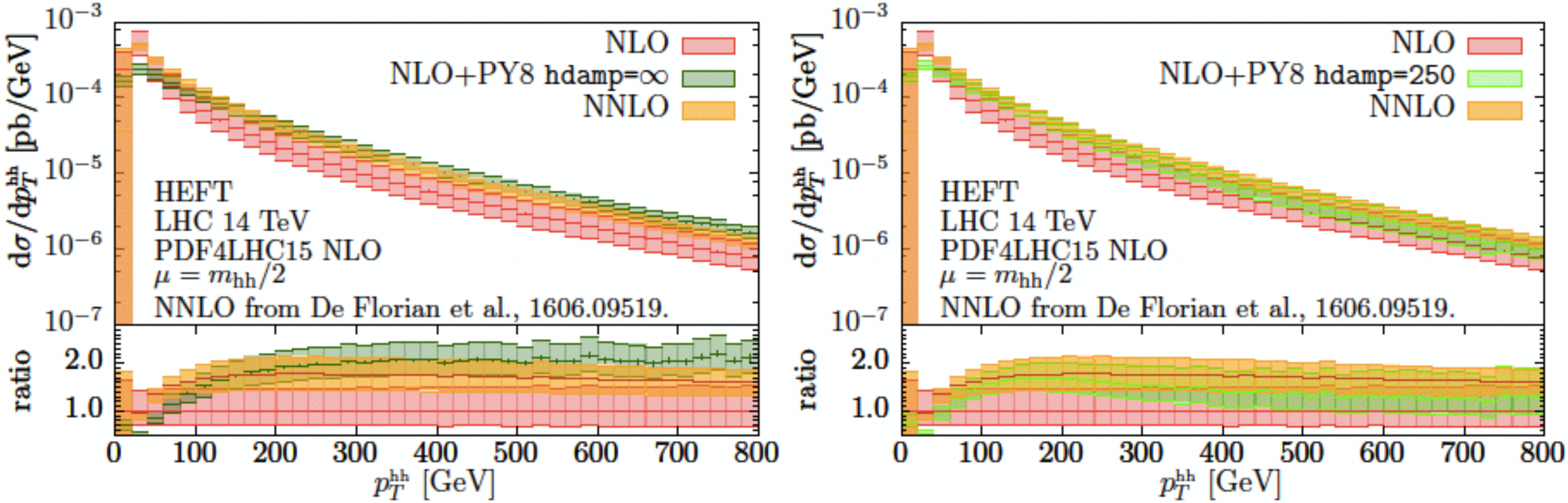
ToDo:

- combine with NNLO HEFT and NNLL resummation
- combination with Herwig7
- phenomenological study with Higgs boson decays
- implementation of BSM effective couplings/operators



BACKUP SLIDES

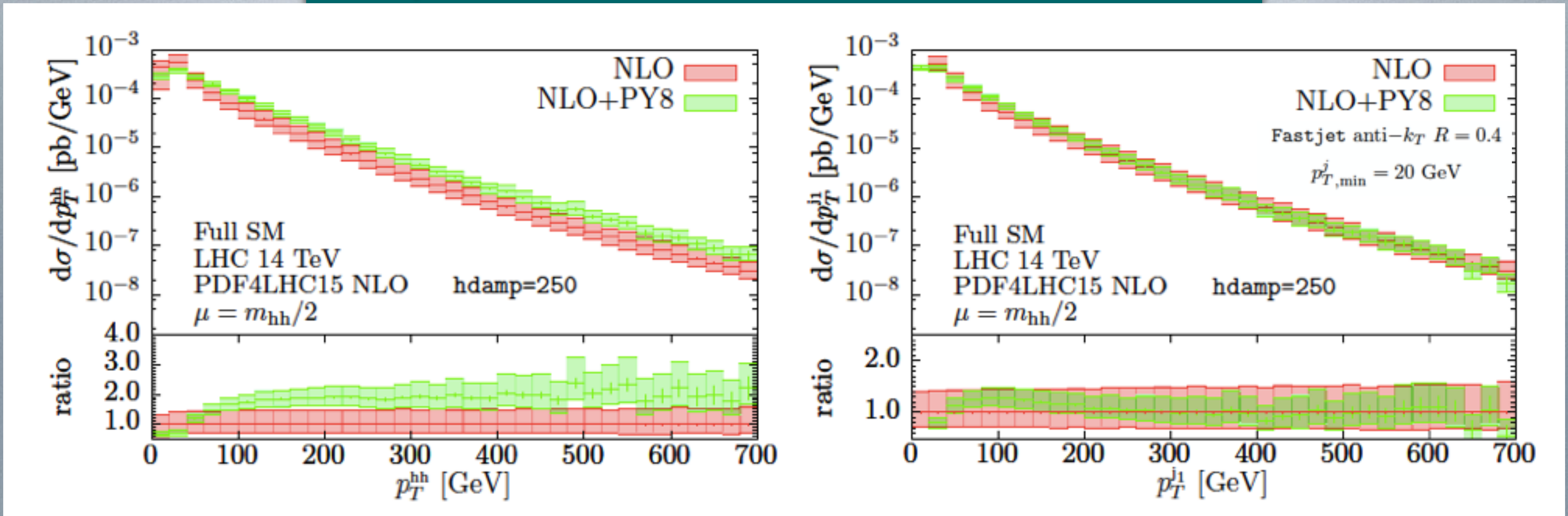
HEFT: comparison to NNLO



$h_{\mathrm{damp}} = \infty$ closer to NNLO at large pTHH

$h_{\mathrm{damp}} = 250\ \mathrm{GeV}$ closer to NLO at large pTHH

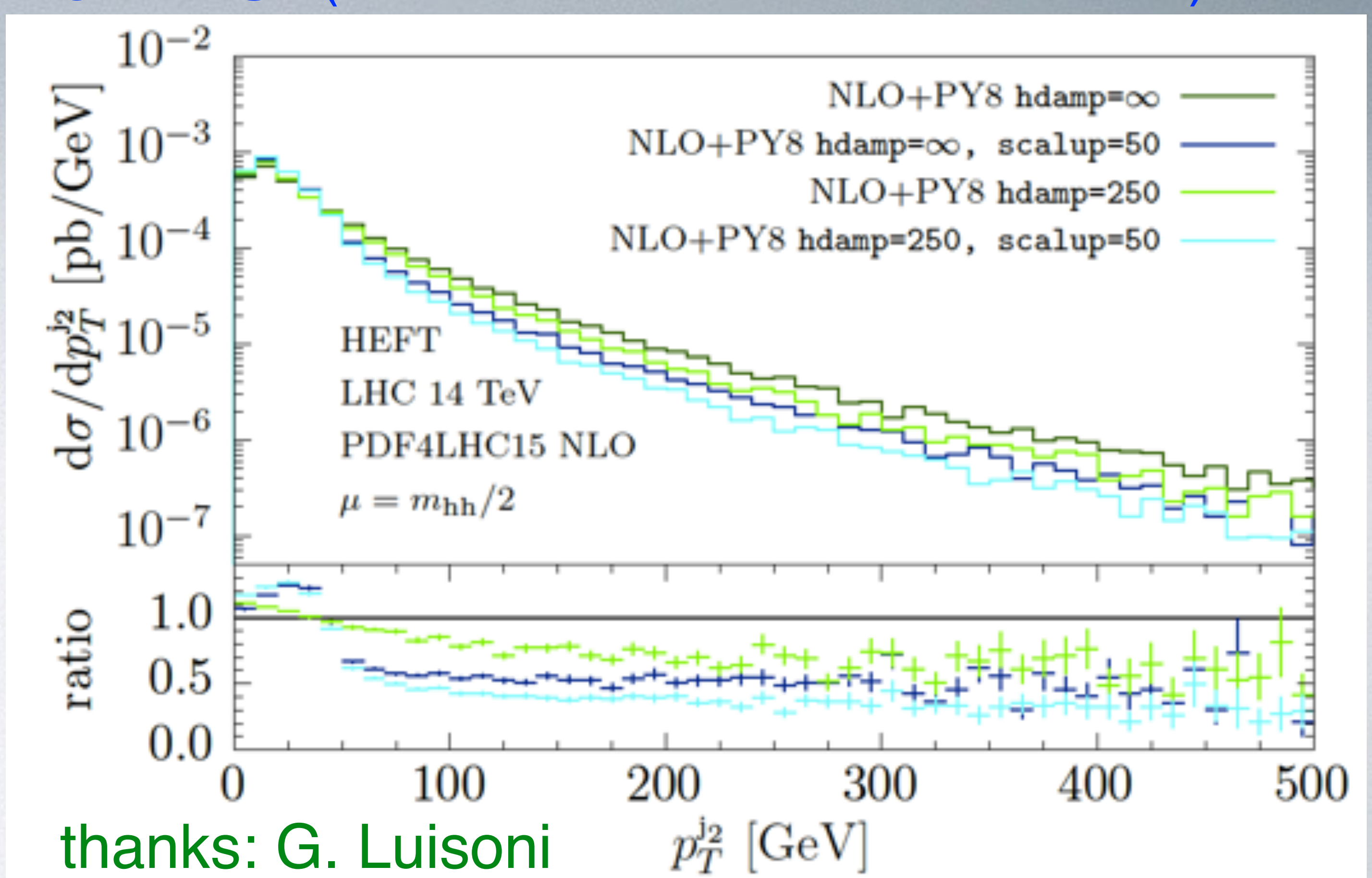
compare fixed order and showered results



leading jet distribution matches onto NLO (one 'hard' emission at ME level)

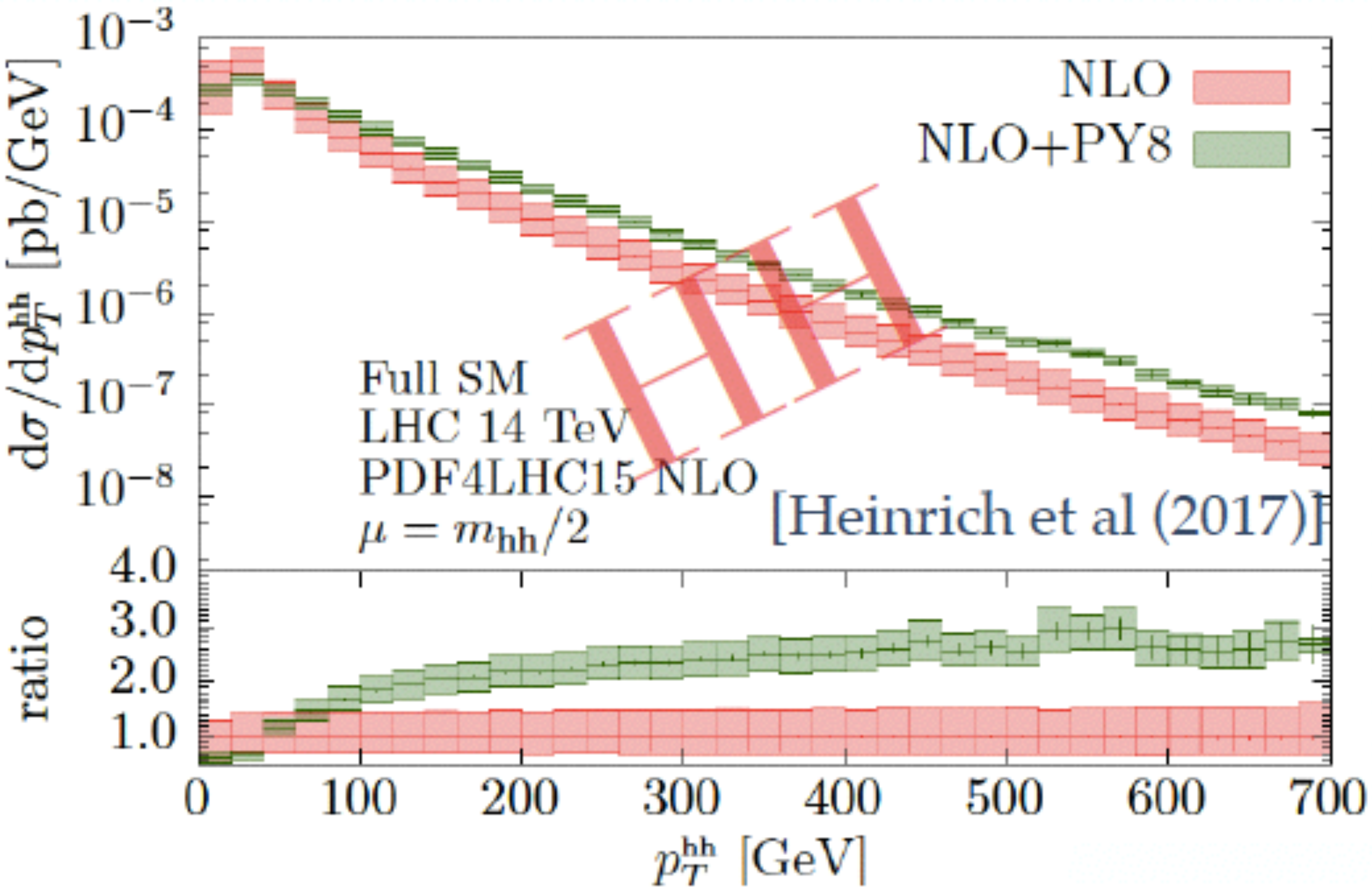
second jet (generated by the shower)

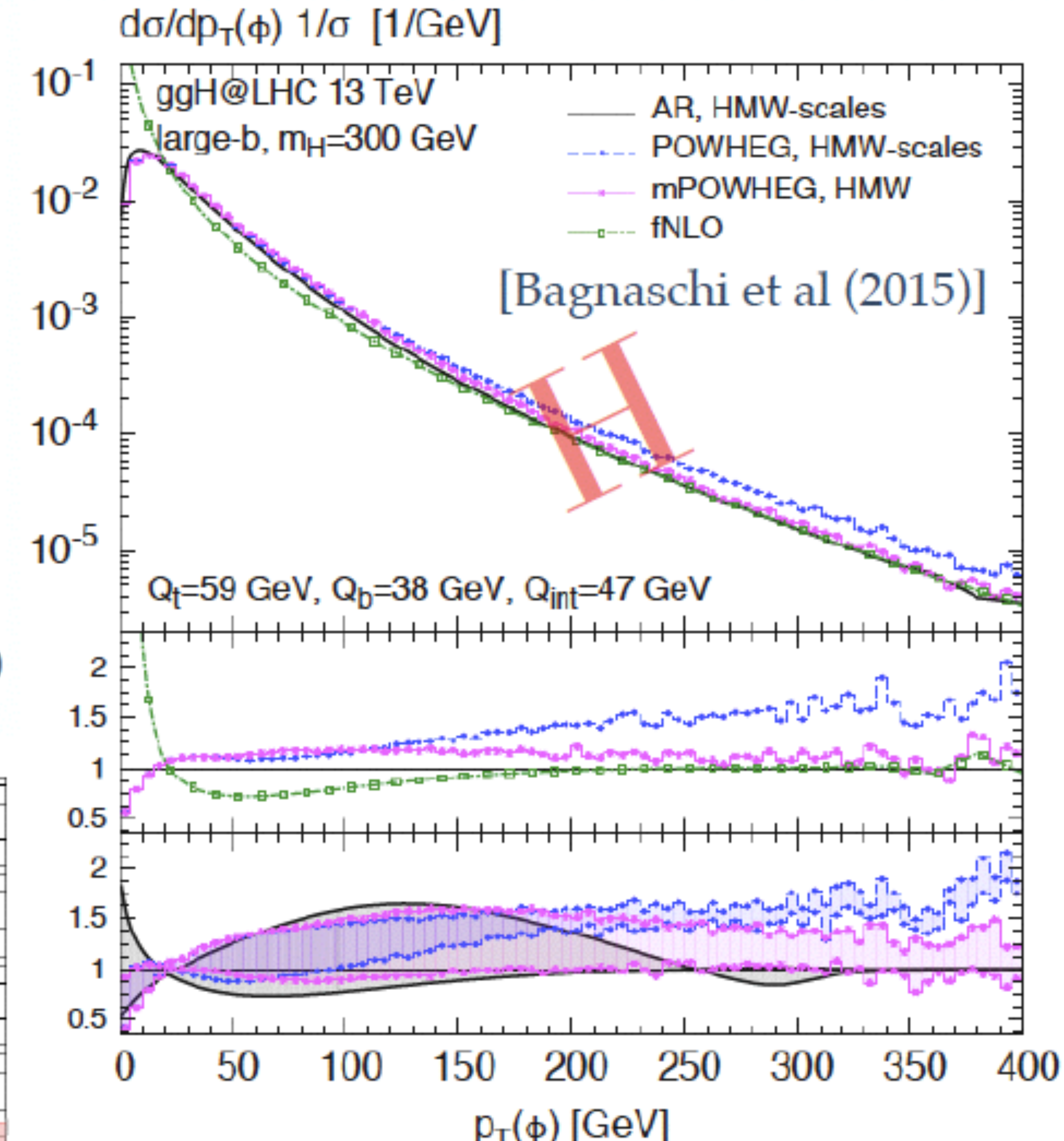
still pretty hard

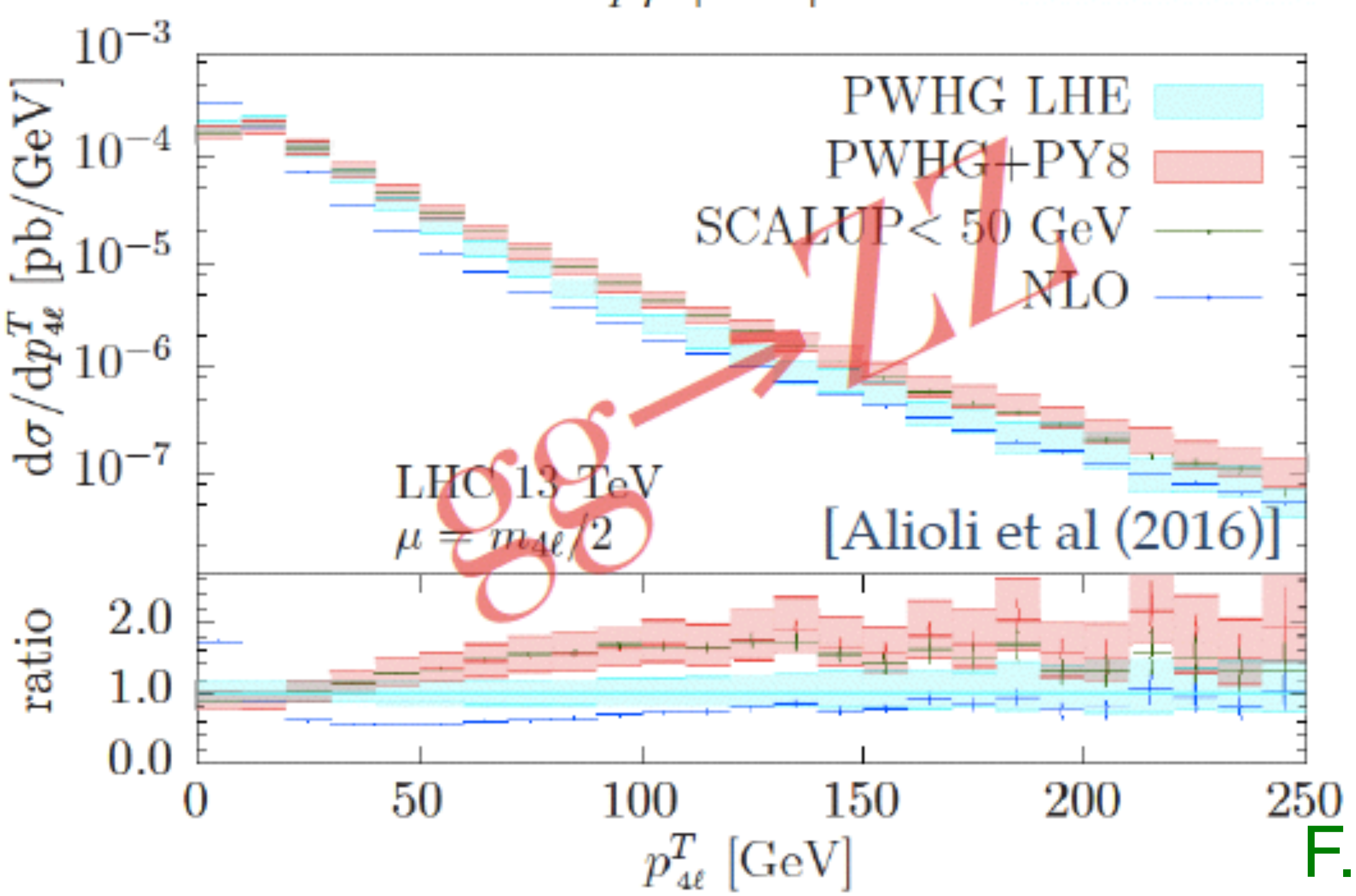


thanks: G. Luisoni

Looking at tails for Higgs physics…



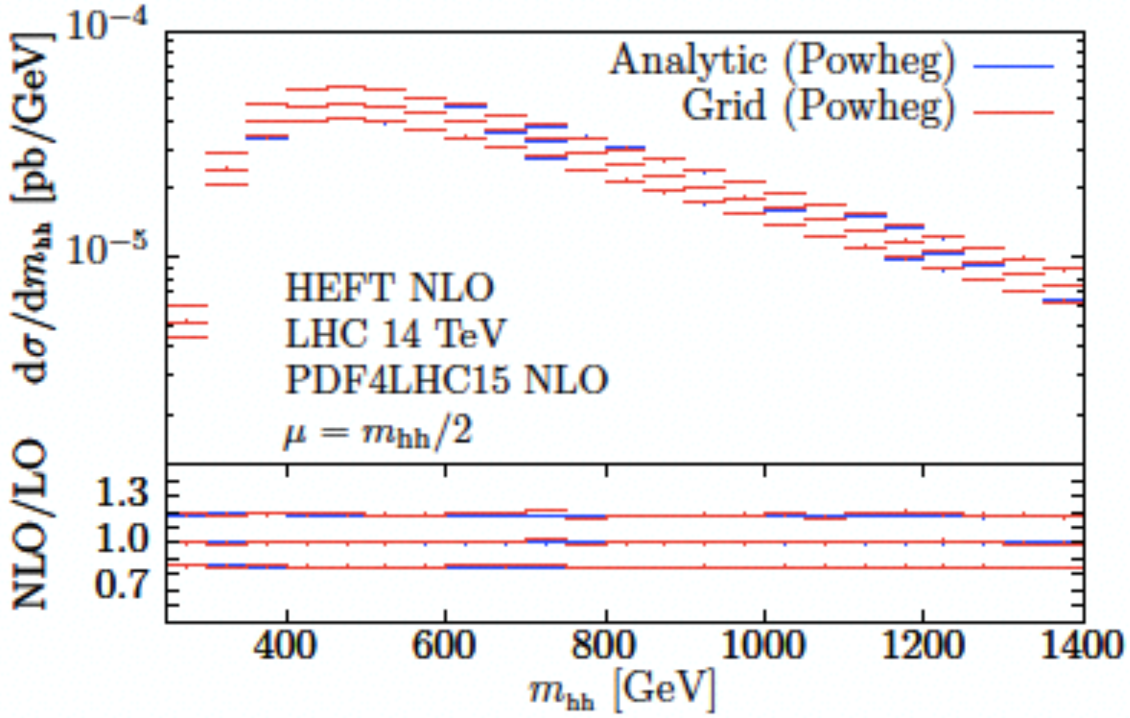


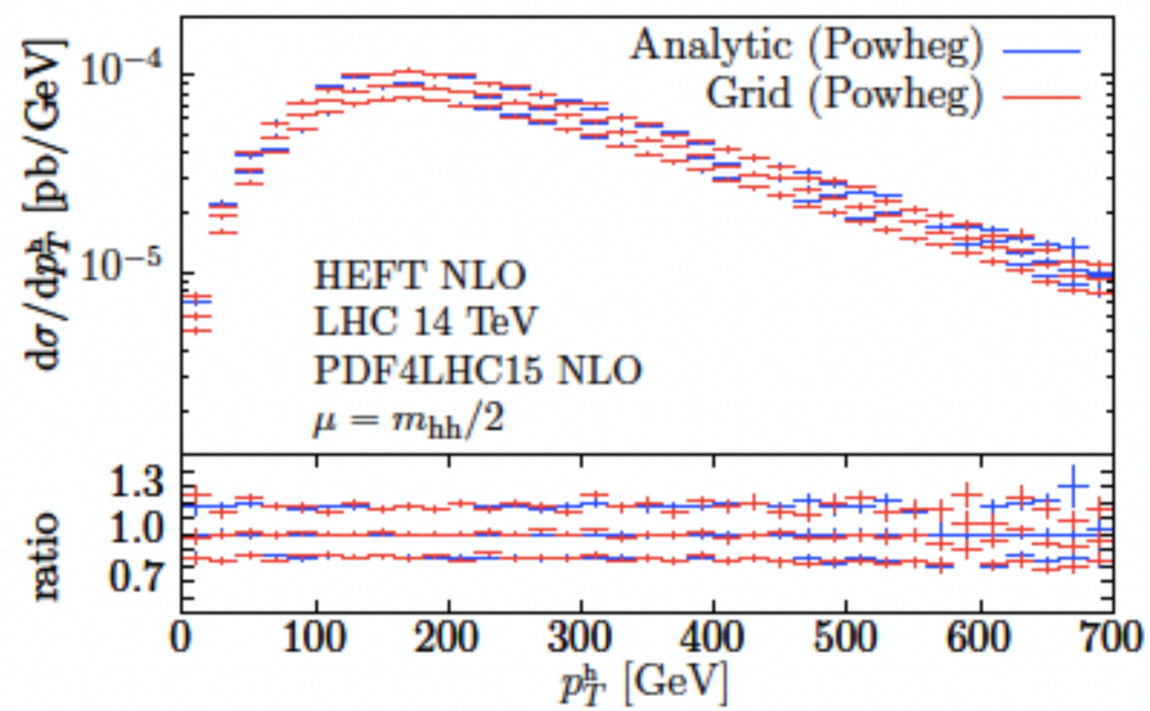


LH: Detailed study of shower effects at large p_T

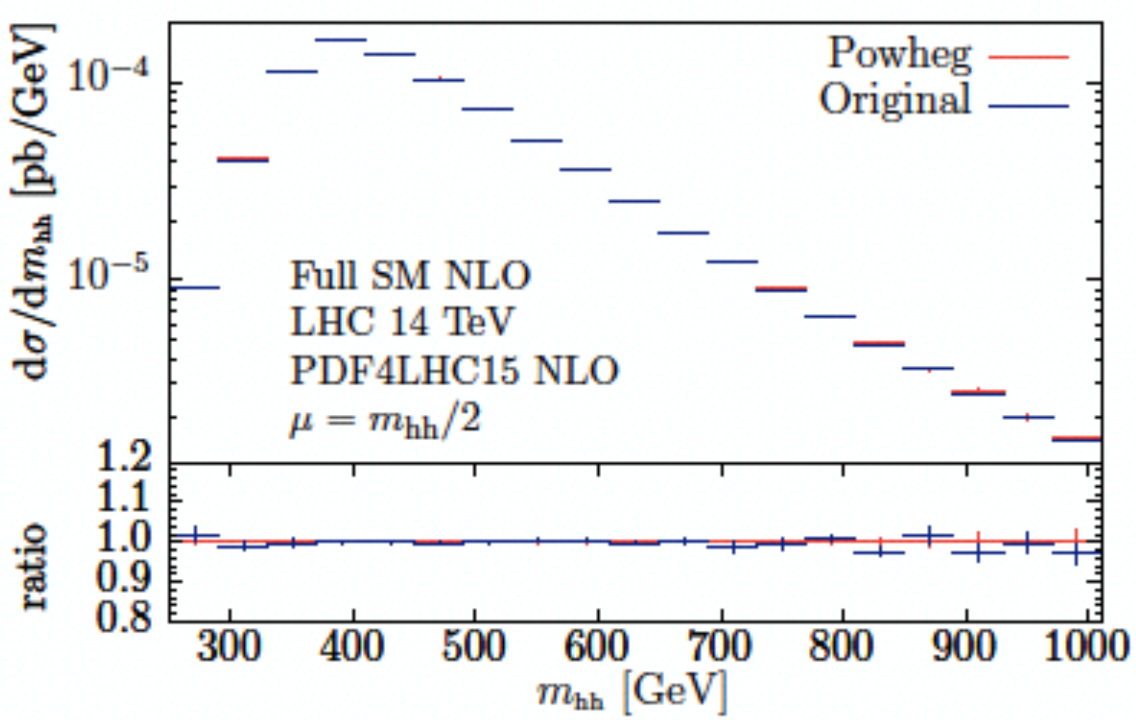
grid validation

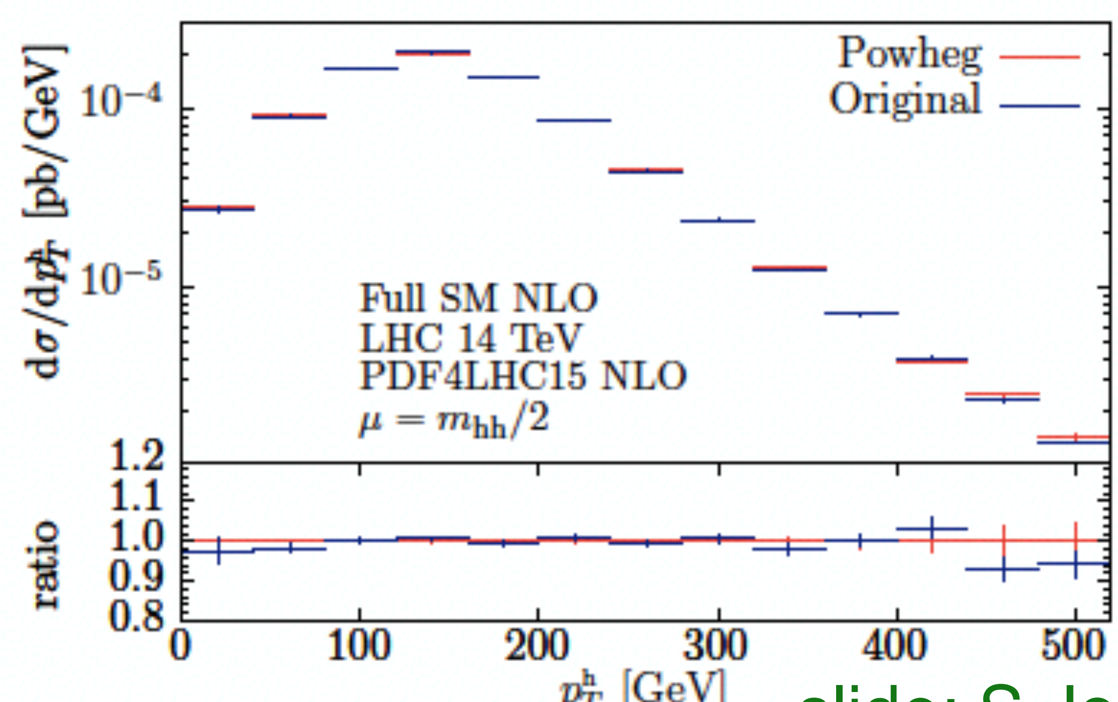
Use HEFT to study validity of grid





Full SM compare `POWHEG` (grid) with our original results



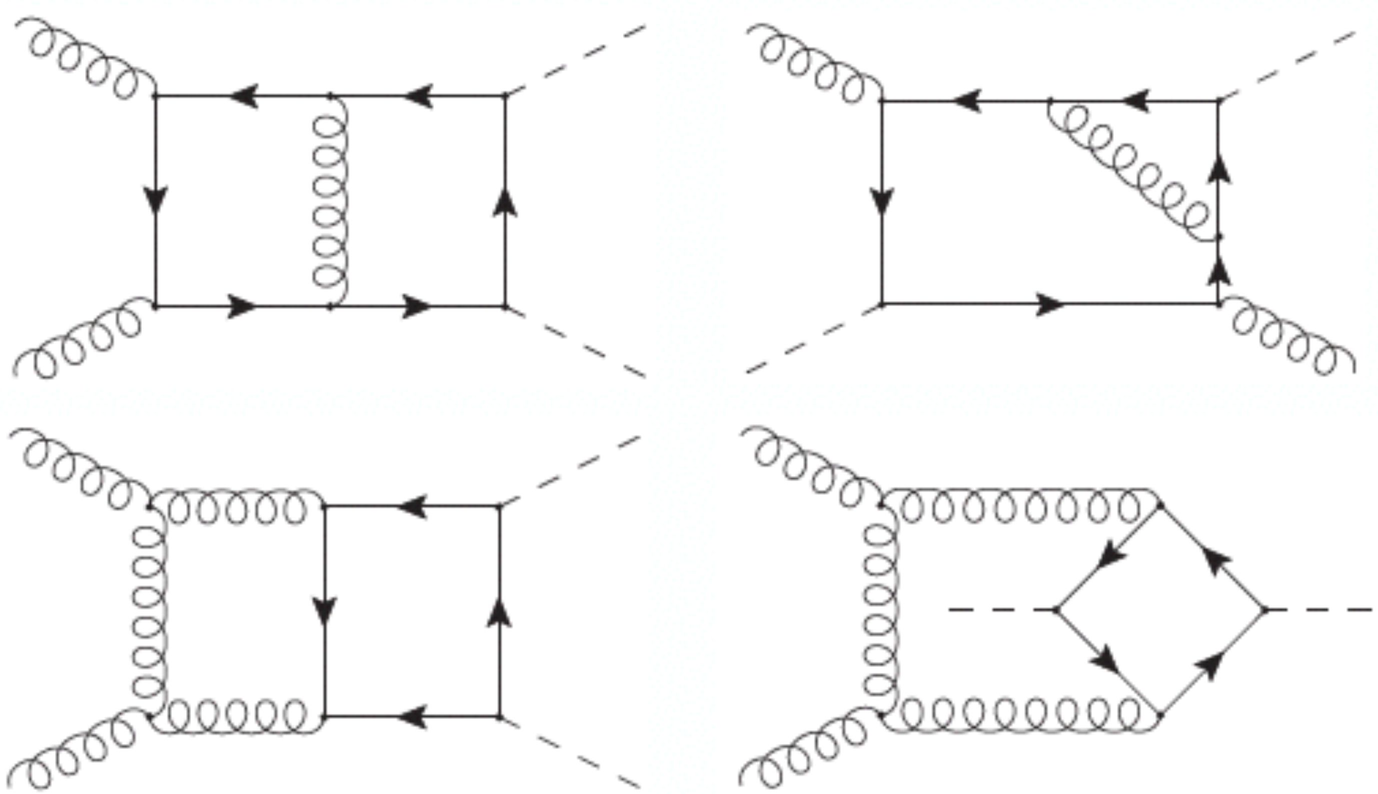


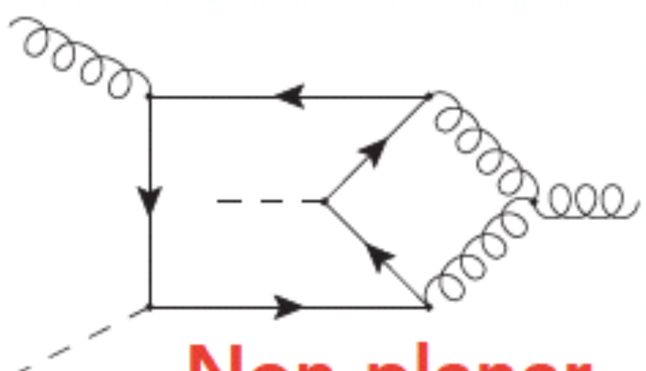
slide: S.Jones

two-loop integrals

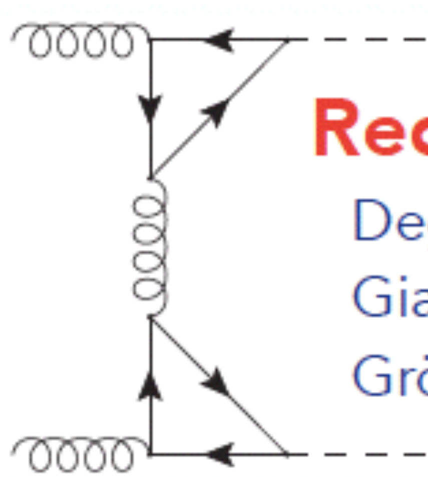
slide by Stephen Jones

Yukawa only (≤ 4-point)





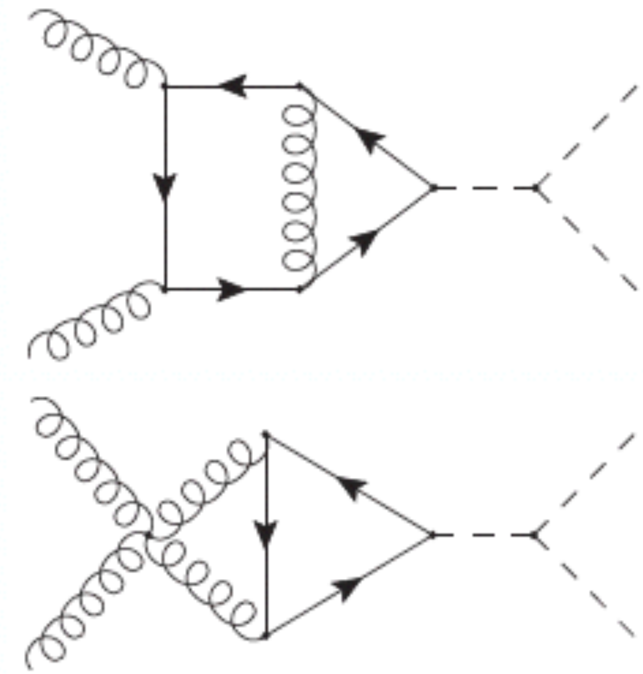
Non-planar



Reducible

Degrassi, Giardino, Gröber 16

Self-coupling (≤3-point)



Integrals Known

$gg \to H$

Spira, Djouadi et al. 93, 95;
Bonciani, P. Mastrolia 03,04;
Anastasiou, Beerli et al. 06;

Many integrals not known analytically, except:

$H \to Z\gamma$ Bonciani, Del Duca, Frellesvig et al. 15; Gehrmann, Guns, Kara 15;